

Development of a 40 MHz Gas Ionization Chamber for Optimization of LHC Luminosity

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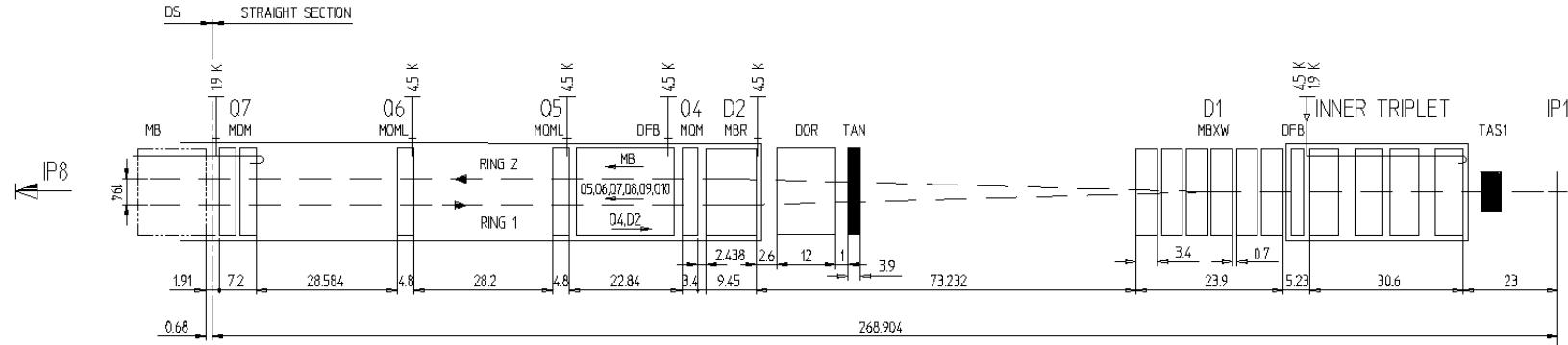
Brief history

- Ion collection mode, average L Jan 1997
- Electron collection mode, 40MHz Nov 1998
- Lumi mini workshop Apr 1999
- CDR Sep 1999
- First SPS H4 beam test Jul 2000
- Second SPS H4 beam test Sep 2001
- Second Lumi mini workshop Nov 2001

Outline

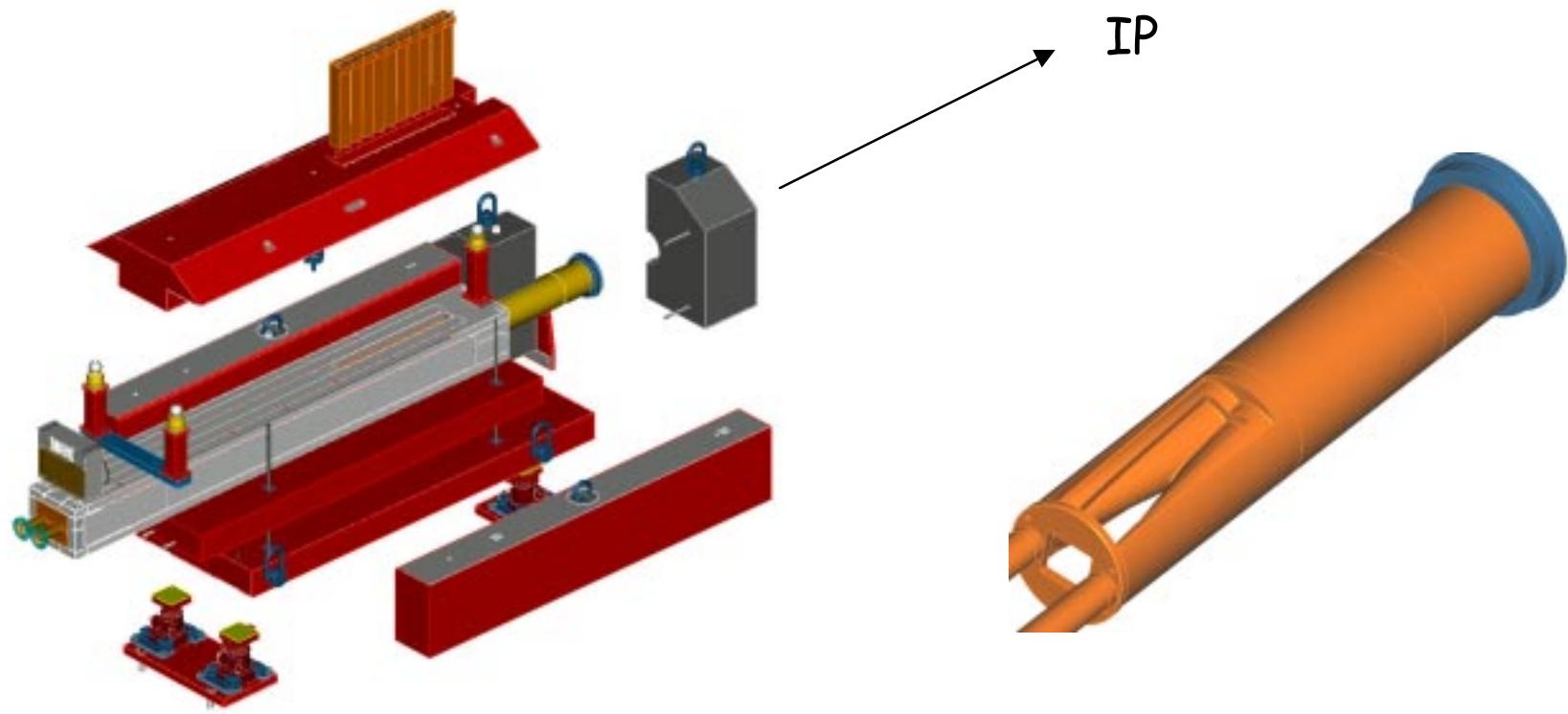
- Review of the concept
- Design requirements and principles
- Hadronic/em shower simulation
- Experimental results

TAN and TAS absorbers in IPs 1 and 5



- The TAS absorbs ~200W of forward collision products that have escaped the beam tube in front of Q1 (mostly charged pions and photons)
- The TAN absorbs ~ 200W of forward neutral collision products (mostly neutrons and photons) and is placed in front of the outer beam separation dipole D2
- Instrument the TAN and TAS to measure and optimize the luminosity of colliding bunch pairs with 40MHz resolution

Exploded view of the neutral absorber and transition beam tube

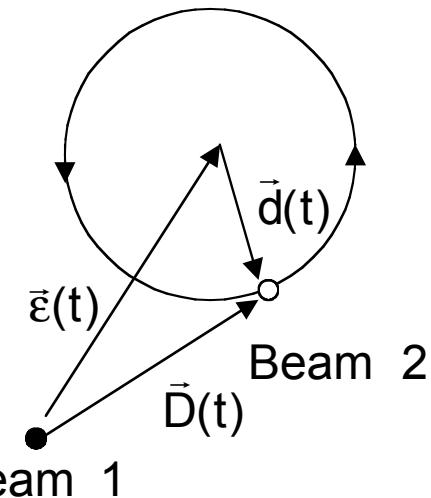


Concept for optimization of luminosity

- An intentional transverse sweep of one beam introduces a time dependent modulation of luminosity
 - ε = error offset amplitude
 - d = intentional sweep amplitude
$$L \approx L_0 - L_0 \frac{\varepsilon d}{2\sigma_*^2} \cos(\omega t - \varphi); \varepsilon, d \ll \sigma_*$$
- Define the detector current
- Integrate to obtain the luminosity and error offset, $0 < t < T$,

$$L_0 = \frac{\int_0^T I(t) dt}{e \alpha \varepsilon_{det} m \sigma_{inel} T};$$

$$\bar{\varepsilon} = - \frac{\hat{e}_x \int_0^T \cos(\omega t) I(t) dt + \hat{e}_y \int_0^T \sin(\omega t) I(t) dt}{\left(\frac{d}{4\sigma_*^2} \right) e \alpha \varepsilon_{det} m \sigma_{inel} T}$$



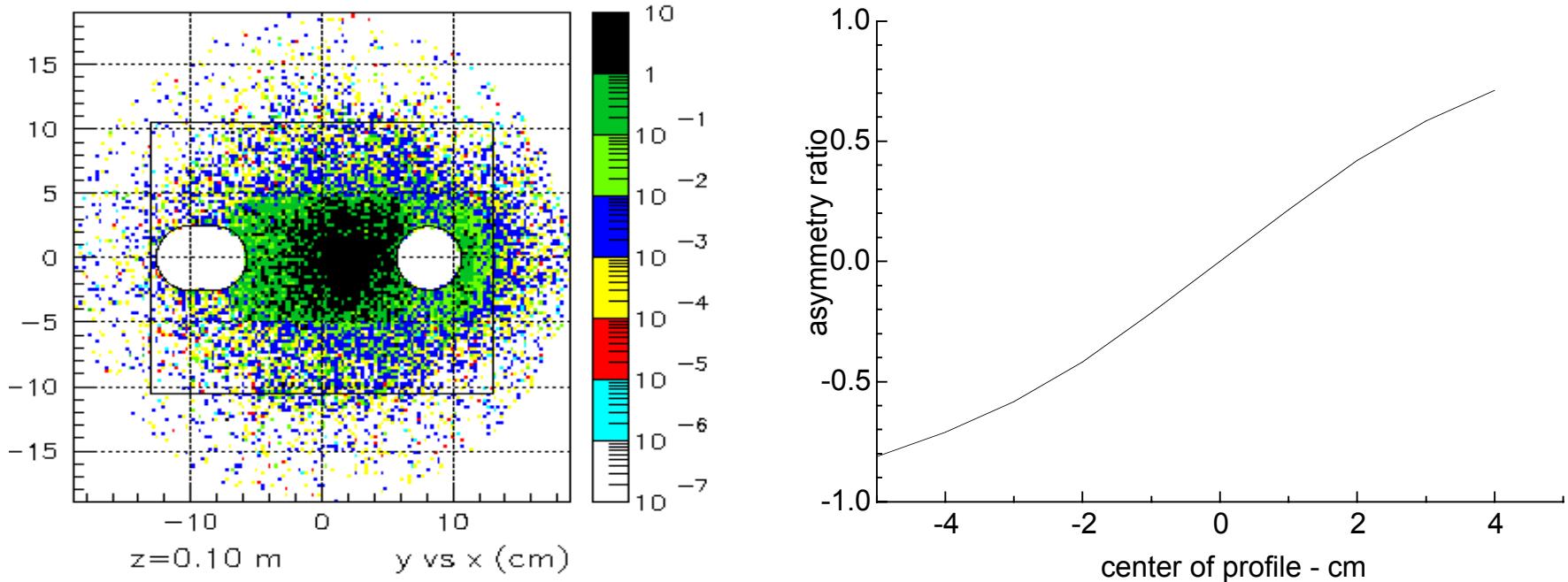
Incident particle fluxes per pp interaction

Particle type	(a) TAN			(b) TAS		
	$\langle n \rangle$	$\langle E \rangle$ (GeV)	$\langle n \rangle \langle E \rangle$ (GeV)	$\langle n \rangle$	$\langle E \rangle$ (GeV)	$\langle n \rangle \langle E \rangle$ (GeV)
Neutral hadrons	.33	2185.	725	.58	261.	152
Protons	.06	1215.	73	.29	292.	83
Charged Pions	.71	125.	88	6.8	159.	1081
Photons	151	4.87	735	8.3	87.	725
Electron/positron	12.5	.66	8.25	-	-	-
Muons	.014	25	.35	.06	33	2
Total			1,630			2,043

- An example: TAN neutrons
- $L = 10^{34} \text{ cm}^{-2}\text{s}^{-1}$, $\sigma_{\text{inel}} = 80 \text{ mb}$ $\Rightarrow 8 \times 10^8 \text{ pp int/s}$
- $\langle n \rangle = 0.33 \text{ neutrons/pp int}$ $\Rightarrow 2.6 \times 10^8 \text{ n/s}$
- $f = 40 \text{ MHz bunch xing}$ $\Rightarrow 6.6 \text{ n/bunch xing}$

The right-left asymmetry ratio is a sensitive function of the crossing angle

- TAN 142 m from IP, xing angle = ± 150 mrad



- Measurement of the asymmetry ratios at the positions of the TAS and TAN on both sides of an IP may allow determination of IP pos. and xing angle

Integration times are sufficiently short to be practical even for the lowest luminosity envisioned (TOTEM)

		Integration time(sec/turns)		
L cm ⁻² s ⁻¹	$\frac{\sigma_L}{L} = 0.01$	$\sigma_\varepsilon = 0.1\sigma^*$	$\sigma_\psi = 1\mu\text{rad}$	$\sigma_{a_x}^* = \sigma^*$
10 ³⁴	6.2x10 ⁻⁵ / 0.7	1.0x10 ⁻³ / 11	2.55x10 ⁻⁴ / 2.9	3.8x10 ⁻³ / 42.6
10 ²⁸	62/ 7.0x10 ⁵	1.0x10 ³ / 1.1x10 ⁷	2.55x10 ² / 2.9x10 ⁶	3.8x10 ³ / 4.26x10 ⁷

- Bunch by bunch measurements increase the integration times by the number of bunches (x2835 for L = 10³⁴, x36 for TOTEM)
- The practical sweep frequency needed for beam-beam separation measurements will determine the integration time at the highest luminosity

Requirements (Lumi mini Workshop, 16-17 Apr. 99)

- Absolute L measurement with $\delta L/L \sim 5\%$ for $L > 10^{30} \text{ cm}^{-2}\text{sec}^{-1}$
- Cross calibration with LHC experiment measurements of L
(every few months)
- Sensitivity of L measurement to variations of IP position
($x^*, y^* < 1\text{mm}$) and crossing angle ($x^*, y^* < 10\mu\text{rad}$) less than 1%
- Dynamic range with "reasonable" acquisition times for 1% precision to cover $10^{28}\text{cm}^{-2} \text{ sec}^{-1}$ to $10^{34}\text{cm}^{-2} \text{ sec}^{-1}$
- Capable of use to keep machine tuned within $\sim 2\%$ of optimum L
- Bandwidth 40 MHz to resolve the luminosity of individual bunches
- Backgrounds less than 10% of the L signal and correctable

Constraints

- Very high peak radiation fluxes and high induced activation over many years of operation, 170 MGy (17GRad)/oper yr

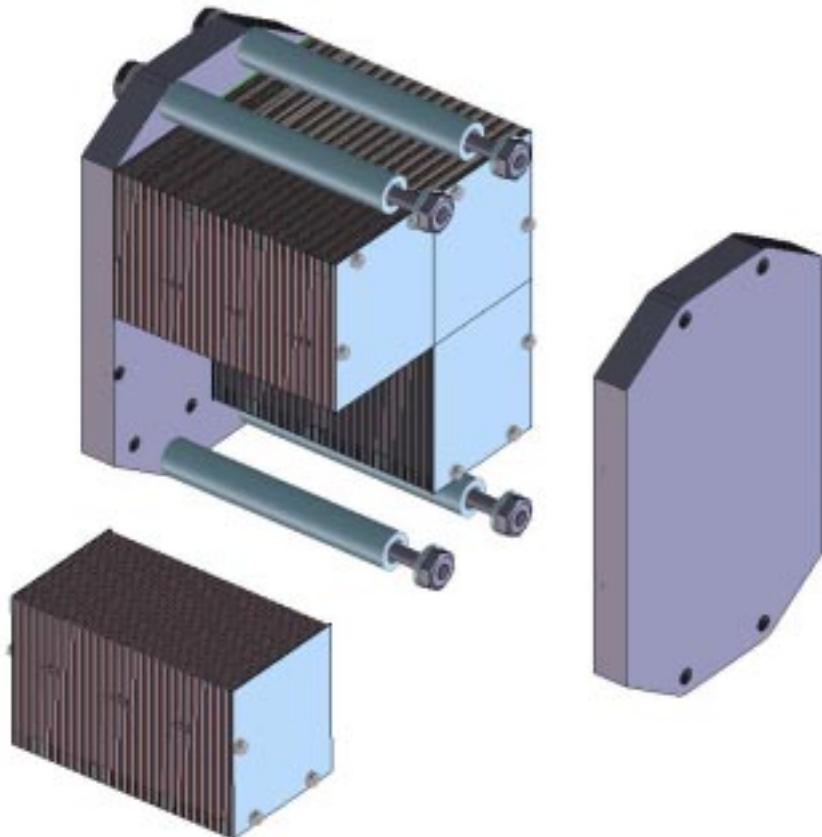
Particle type	Peak Flux($\text{cm}^{-2}\text{sec}^{-1}$)
Charged hadrons	4.7×10^8
Electron/positron	7.5×10^{10}
Photons	1.1×10^{12}
Neutrons	4.6×10^9

- Size limited to $80 \times 80 \text{ mm}^2$ by beam-beam separation at the TAN
- ~ 25 ns clearing time between bunch crossings
- Sensitivity to a single pp interaction with good S/N ratio, ~ 270 mips in $40 \times 40 \text{ mm}^2$

The technical solution ...

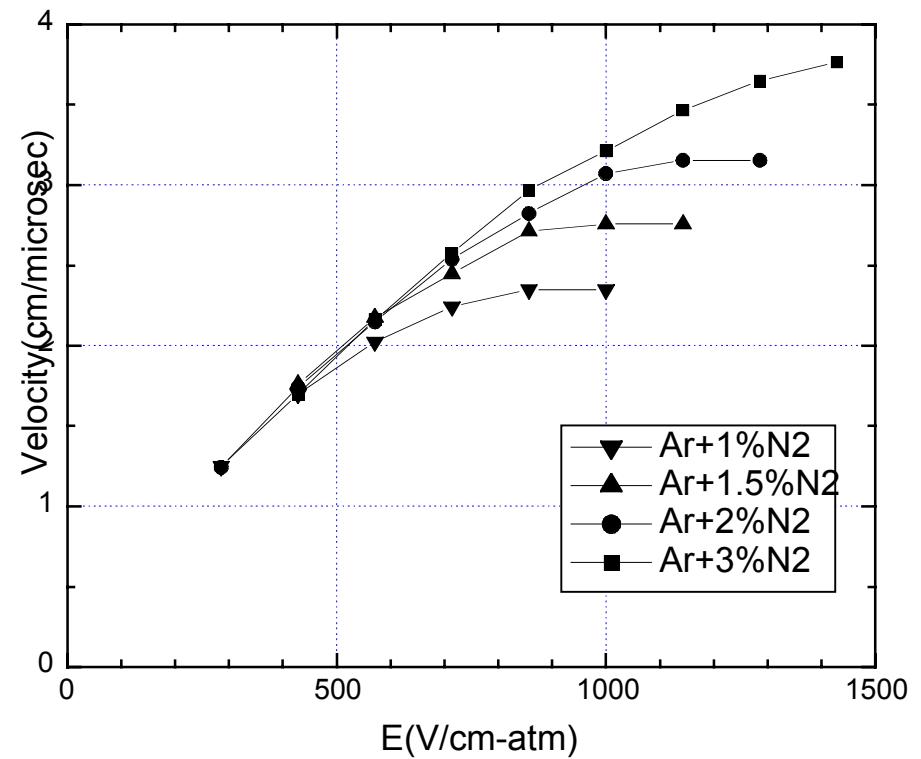
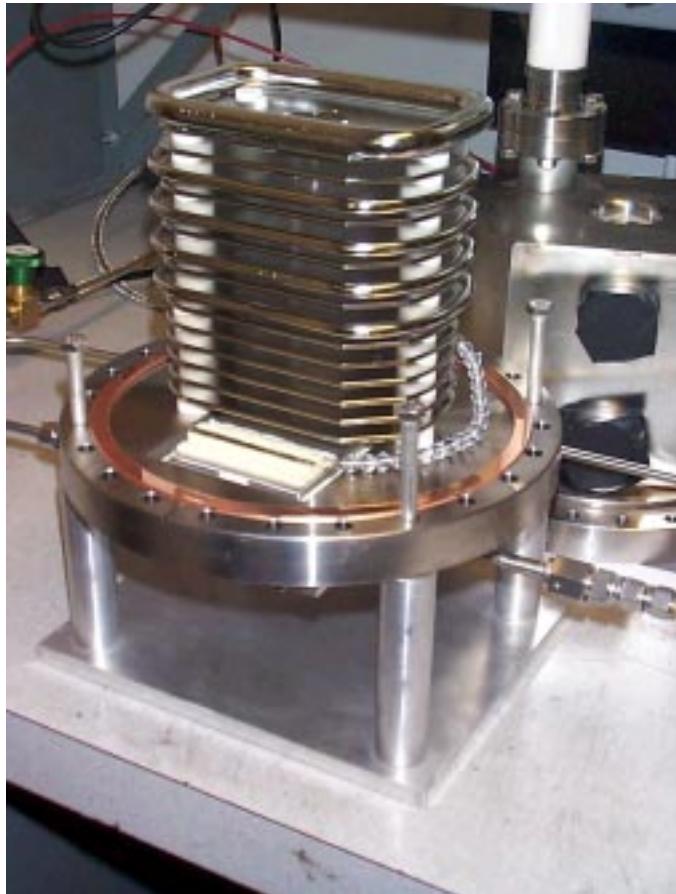
- Segmented, multi-gap, pressurized gas ionization chamber constructed of rad hard materials
- 3-11 atmospheres Ar + 2%N₂ gas mixture, e⁻ drift velocity 3.2 cm/ μ s
- Low noise bi-polar transistor pre-amplifier "cold" cable termination, ENC _{δ} ~ 1,824 e⁻
- Pulse shaper, τ = 2.5 ns
- 3 m radiation hard cable between ionization chamber and front end electronics, radiation dose to electronics < 100 Gy/oper yr
- S/N ~ 5 for single pp interaction

Ionization chamber



- 60 gaps, 10 parallel \times 6 series
- segmented into quadrants
- 0.5 mm gap spacing
- copper, ceramic construction

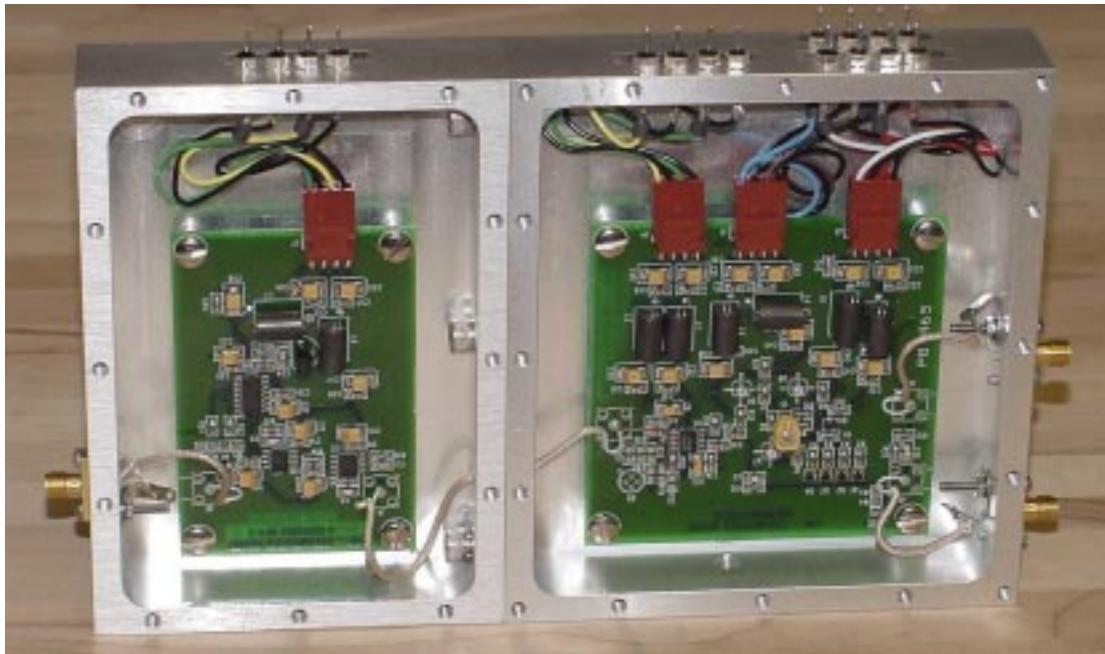
Electron drift velocity versus E/p and N_2 fraction



Parameters for an LHC ionization chamber module

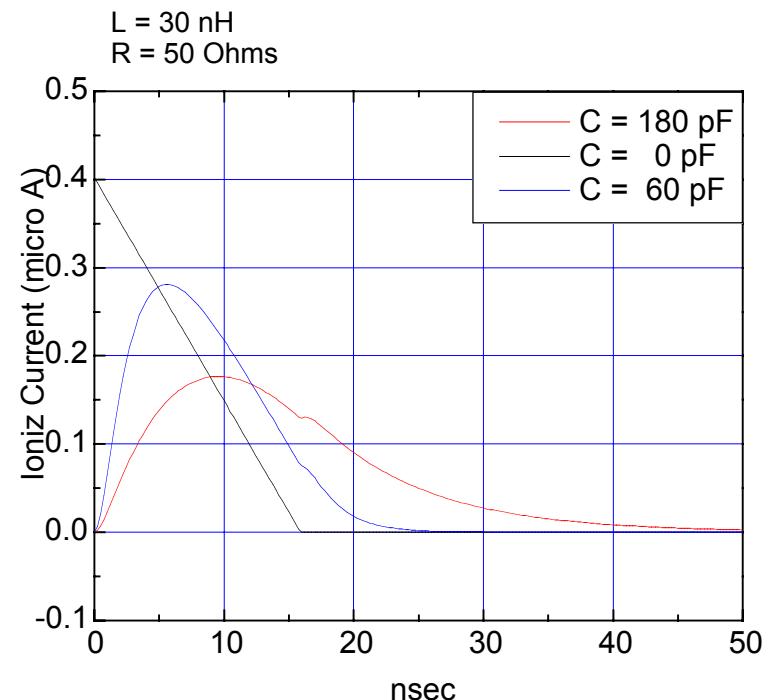
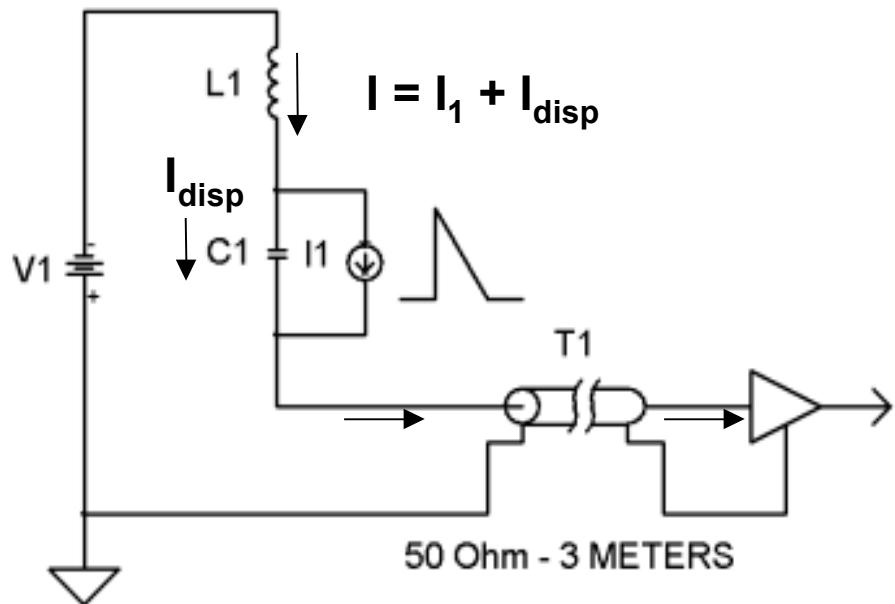
• Active area(1 quadrant)	40mm x 40mm
• Plate gap	0.5 mm
• No. of gaps	60 (electrically 10 parallel x 6 series)
• Capacitance/gap	28.3 pF
• Gas	Ar+N ₂ (1%), 4x760 Torr
• Gap voltage	150 V
• Elec gap transit time	21.7 nsec
• Bunch freq/Rev freq	40.079 MHz/11.2455 kHz
• Bunch structure	12x(3x81+2x8+38) = 3,564
• Inel pp int/bunch xing@10 ³⁴	20
• mip per pp int	268
• mip per bunch xing@10 ³⁴	5.35x10 ³
• Electron/ion pairs/cm-mip	388
• Ioniz e-/pp int	5.2x10³ (1 gap) 5.2x10⁴ (10 gaps)
• Ioniz e-/bunch xing@ 10 ³⁴	1.04x10 ⁵ (1 gap) 1.04x10 ⁶ (10 gaps)

An analog board has been fabricated and shown to meet the bandwidth and noise requirements



- Delta function noise charge
 - $\text{ENC}_\delta = 1824 \text{ e}^-$
- Triangular pulse noise charge (20ns)
 - $\text{ENC}_\Delta = 5107 \text{ e}^-$
- Ballistic deficit
 - $\sigma = 3.0 \pm 0.5$
- $S = 2.6 \times 10^4 \text{ e}^-$ for 1pp interaction
 - $\Rightarrow S/N > 5$
- Transfer function =
 $0.45 \times 10^{-3} \text{ mV/e}^-$

Excitation of normal modes of the ionization chamber broaden the current pulse



I_1 = ionization current (electrons)
 C_1, L_1 = ionization chamber capacitance
 and inductance

Hadronic/em showers

- The hadronic energy incident on the TAN per pp interaction in LHC is ~ 750 GeV
- The flux of mips at the shower maximum in the TAN is \sim linear function of incident hadron energy
- \Rightarrow single 300-450 GeV protons from SPS can be used for realistic tests of response of detector to single pp interactions in LHC
- The MARS code (N. Mokhov) is used for shower simulations of LHC and SPS H4 test beam conditions

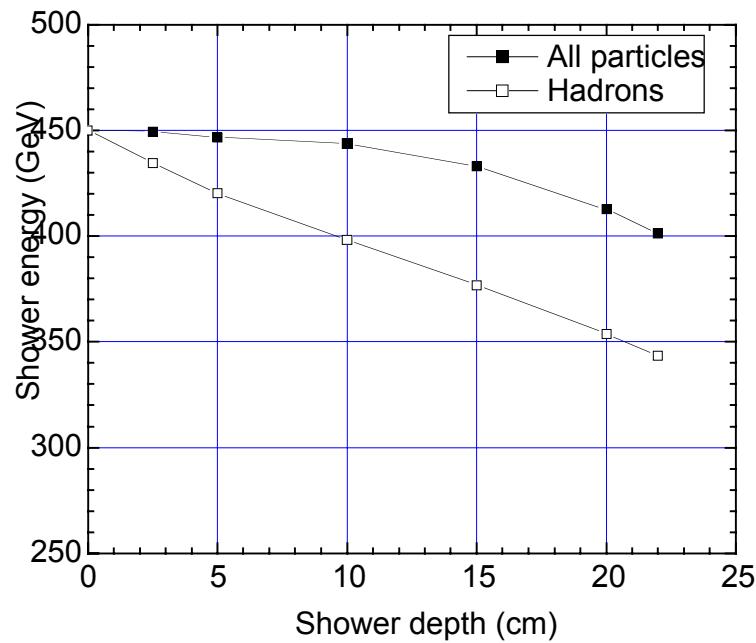
Use the MARS code to

- Understand the energy flow in hadronic/em showers
- Understand the energy deposition by hadronic/em showers
- Estimate the ionization chamber signal from the flux of ionizing radiation

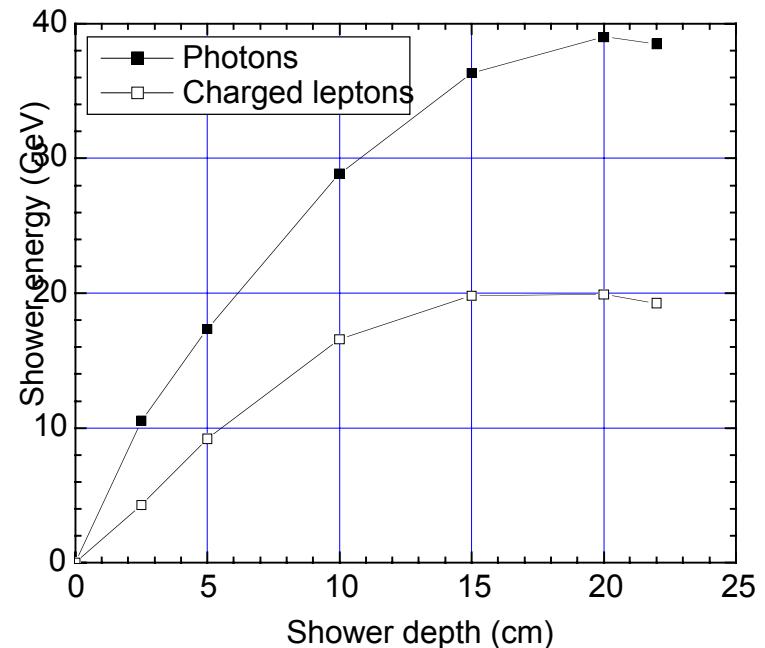
Shower energy is carried predominantly by hadrons

Primary proton energy = 450 GeV

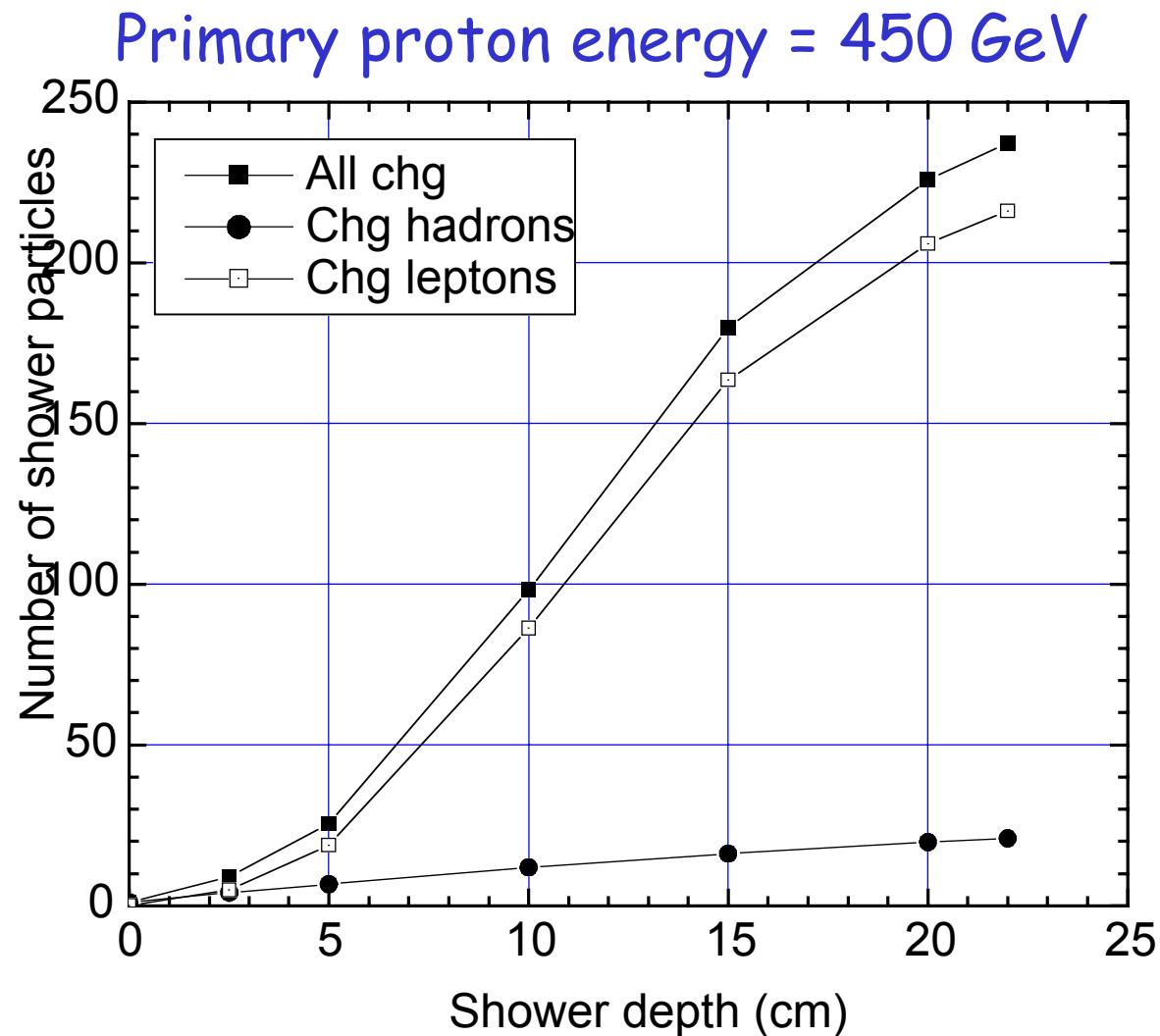
(a) Hadrons



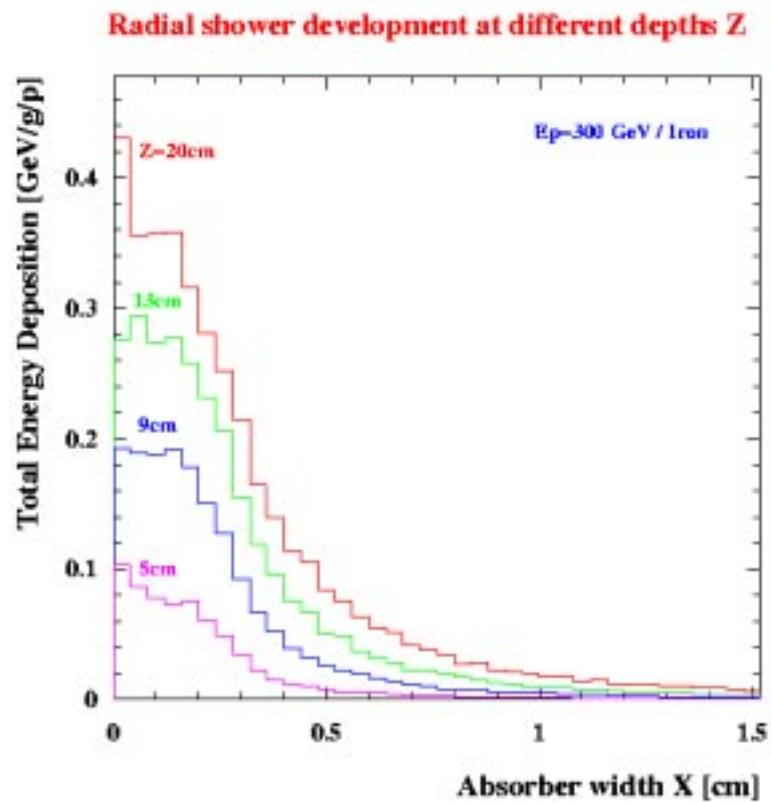
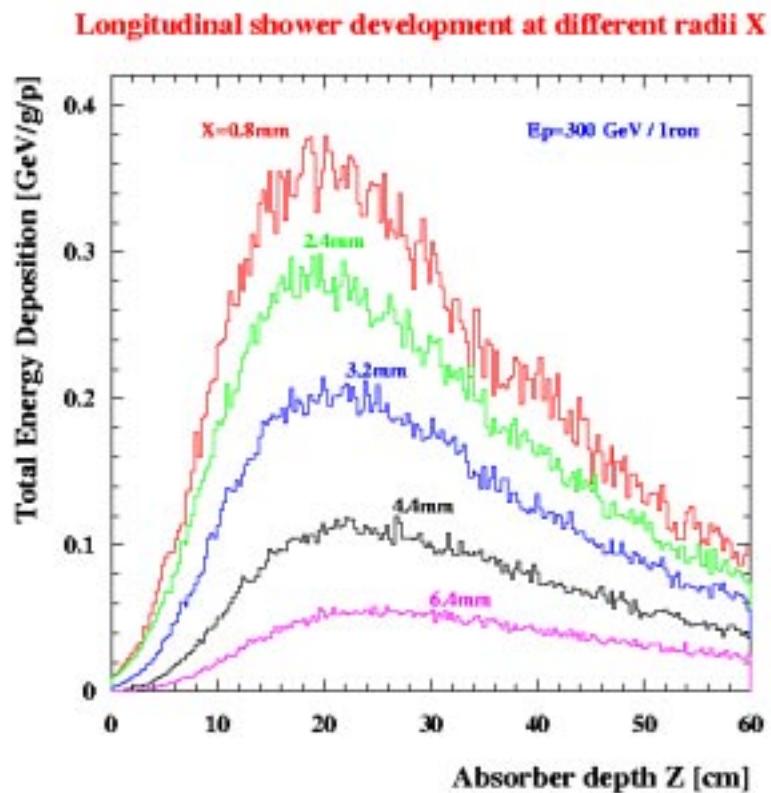
(b) Charged leptons and photons



The charged particle flux (and ∴ energy deposition) is dominated by leptons (mostly e^+e^-)



Ionization energy deposition, $E_p = 300 \text{ GeV}$



Flux and mean energy of particles near the shower maxima of 300 and 450 GeV primary protons

(a) 300 GeV proton

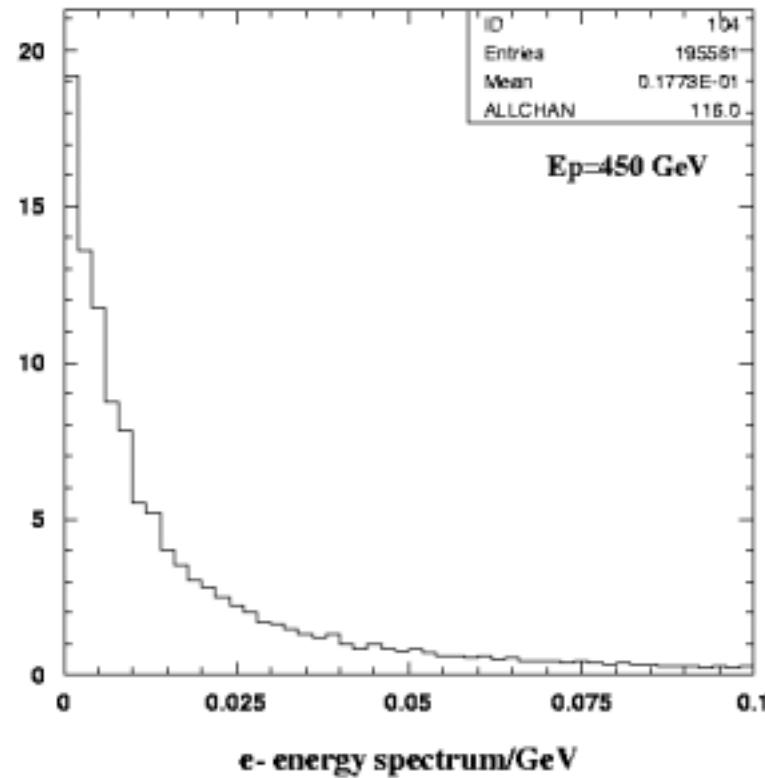
particle	Flux per proton	Mean energy, MeV
e ⁻	84.6	73.0
e ⁺	55.4	108.0
π^-	5.0	5,376
π^+	5.7	6,440
K ⁻	0.50	6,892
K ⁺	0.59	8,501
p	3.4	35,795
n	17.0	1,970
γ	1,738	14.4
All chg.	155.2.0	-

(b) 450 GeV proton

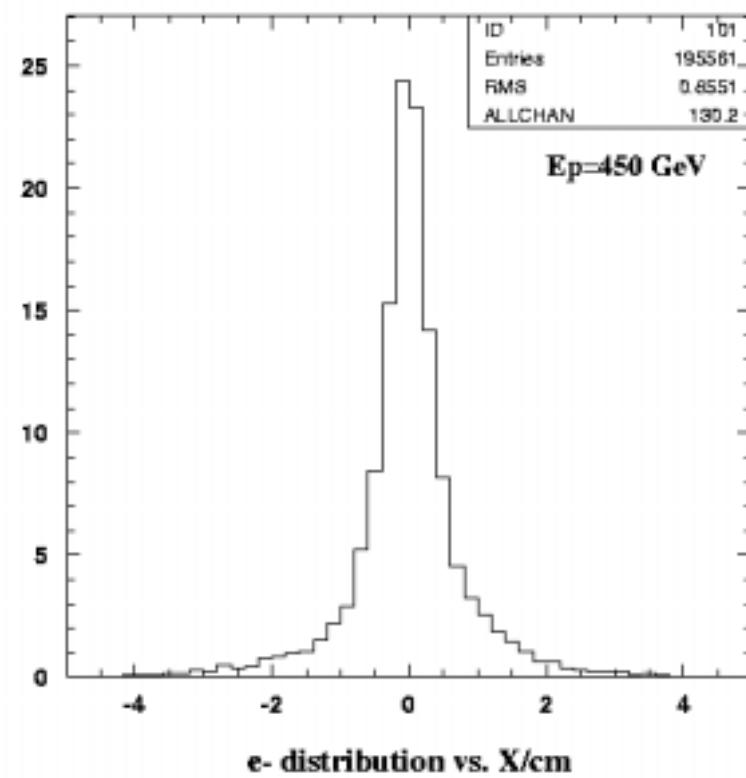
particle	Flux per proton	Mean energy, MeV
e ⁻	130.2	75.2
e ⁺	85.9	109.8
π^-	6.9	6,500
π^+	8.0	7,820
K ⁻	0.74	7,988
K ⁺	0.78	10,812
p	4.4	39,031
n	23.2	2,121
γ	2743.5	14.0
All chg.	237.0	-

Shower electrons at maximum energy deposition

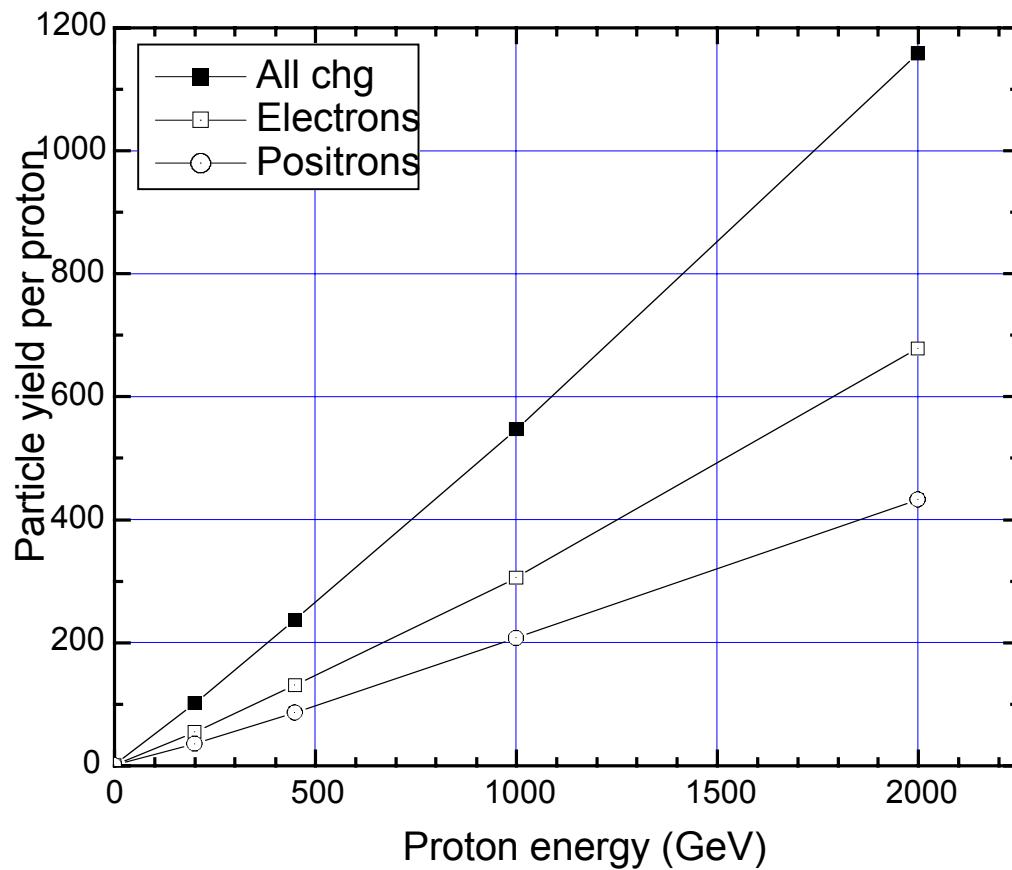
Energy distribution



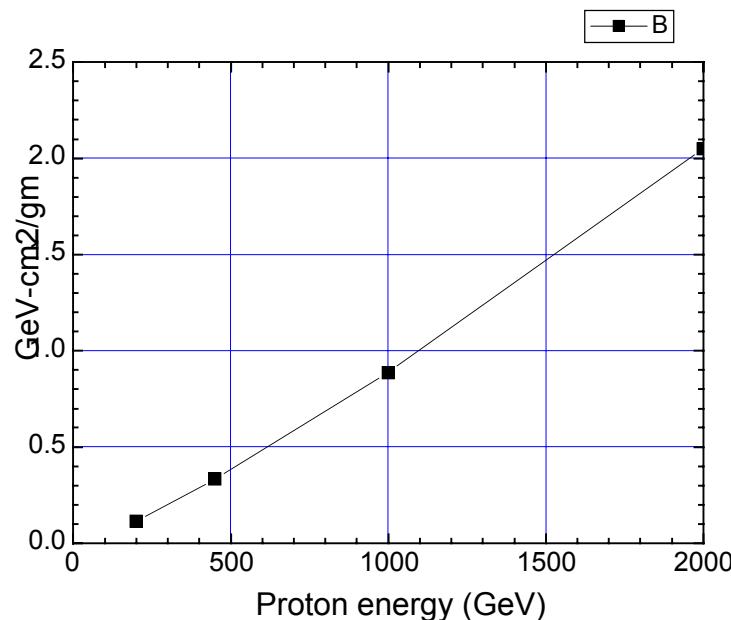
Transverse distribution



Particle yield at the shower maximum is
nearly a linear function of E_p



The energy deposition and flux of mips are nearly linear functions of primary hadron energy



- On average, $dE/dx = 1.45 dE/dx_{min}$
- Flux of mips = energy deposited(GeV-cm²/gm) / dE/dx_{min} (GeV-cm²/gm)
- The ionization produced in the chamber and the anticipated amplifier output are easily calculated from the flux of mips

Predicted signal at shower maximum in 300 GeV proton beam

- 6 atmos Ar+2% N₂ => $6 \times 97 = 582$ electron-ion pairs/cm-mip
- Ten 0.5mm gaps => $0.5 \times 582 = 291$ electrons/mip
- 231 mips/p at shower max => 6.7×10^4 electrons/p
- Transfer function 0.45μV/e
- Ballistic deficit ~ 3±0.5
- Cable attenuation = 20%
- Expected signal
=> $0.5 \times 6.7 \times 10^4 \times 0.45 \times 10^{-6} \times 0.8 / 3 = 4.0 \pm 0.8$ mV

Schematic of setup in SPS H4

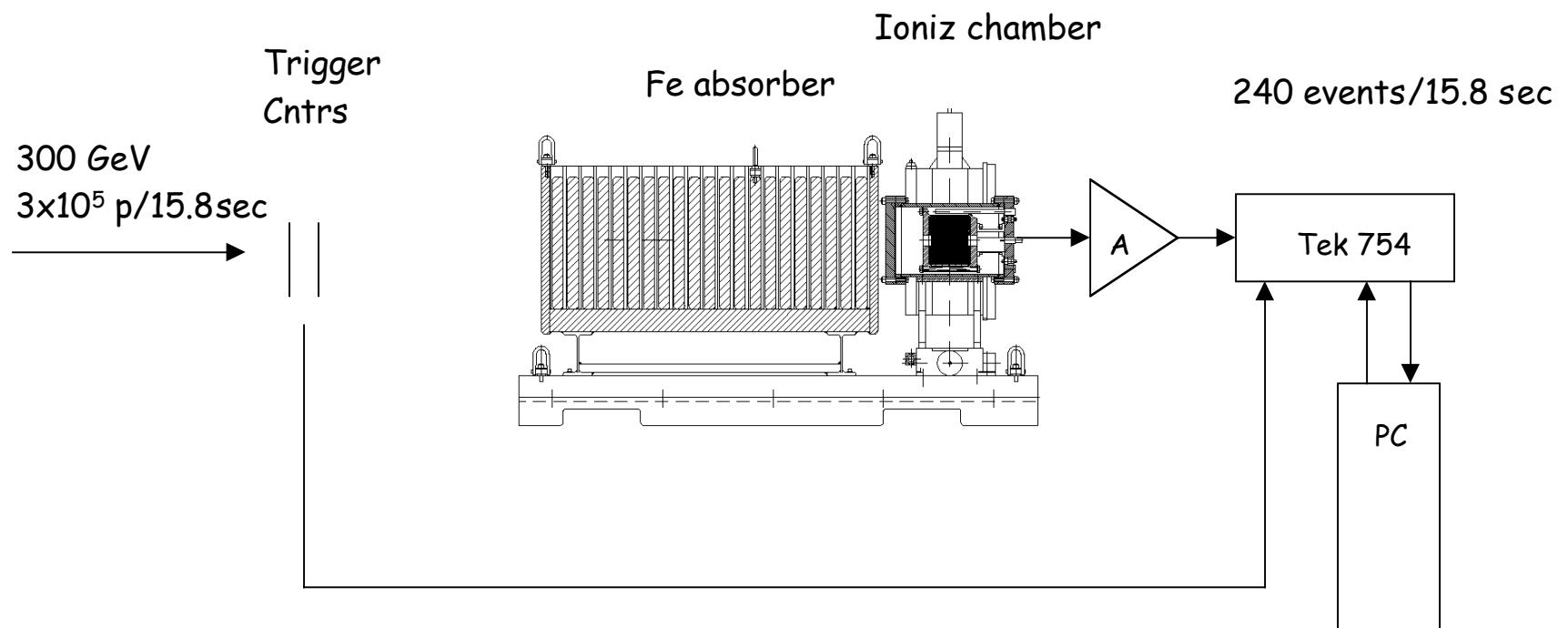
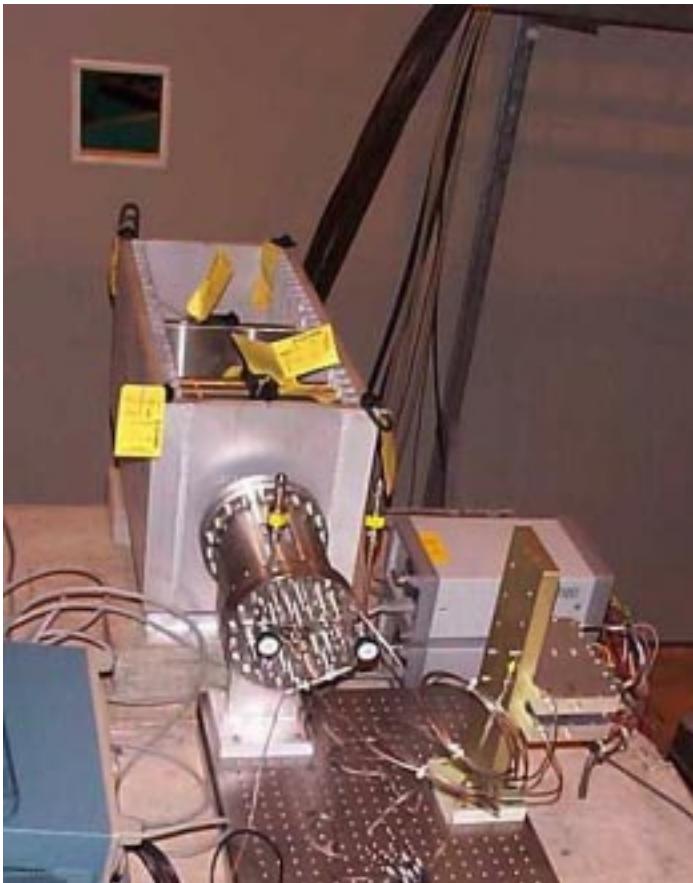
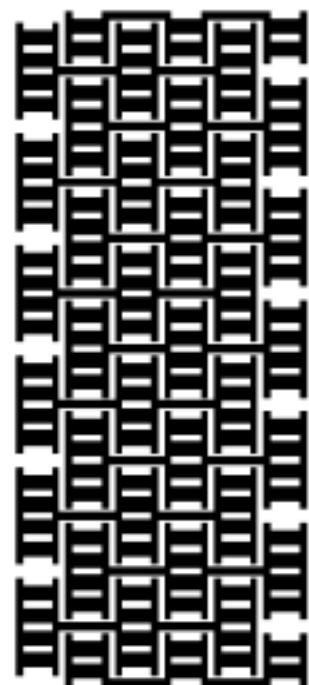


Photo of the setup in SPS H4 300 GeV proton beam,
Sep 2001



Ionization chamber quadrants

Bias board



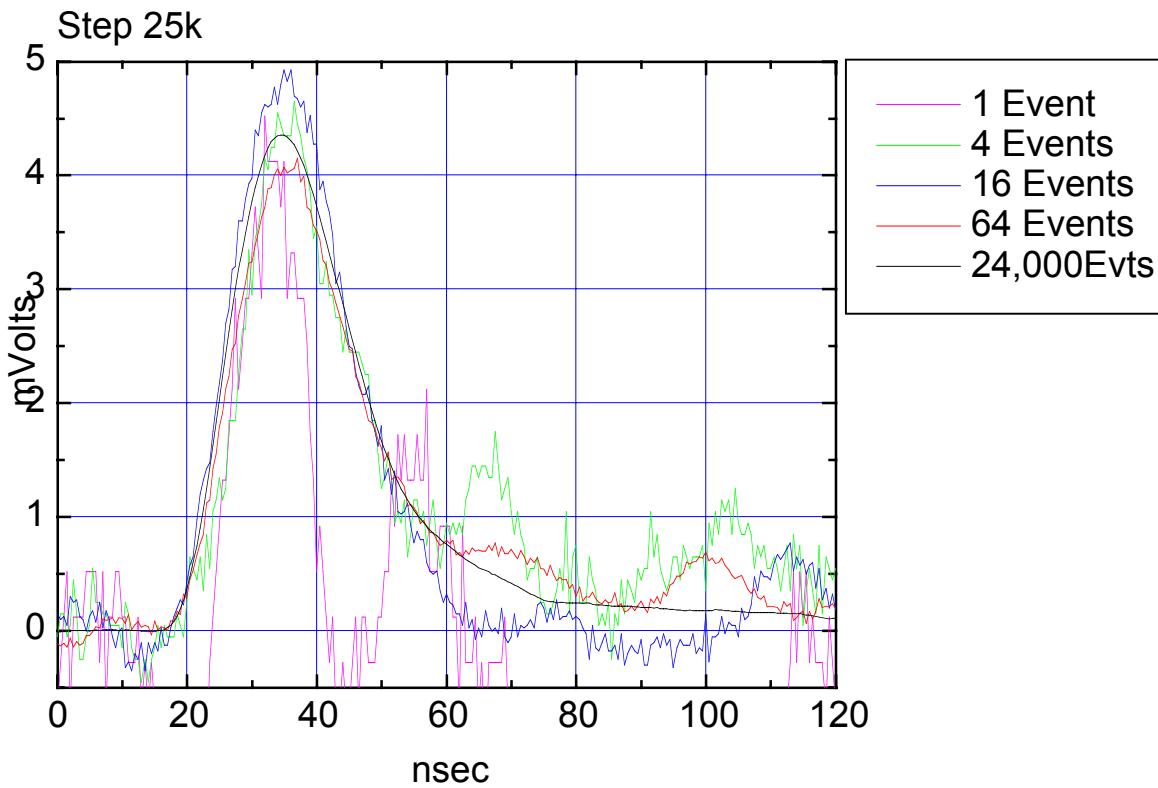
Two quadrants with bias board and capacitors



Experimental results

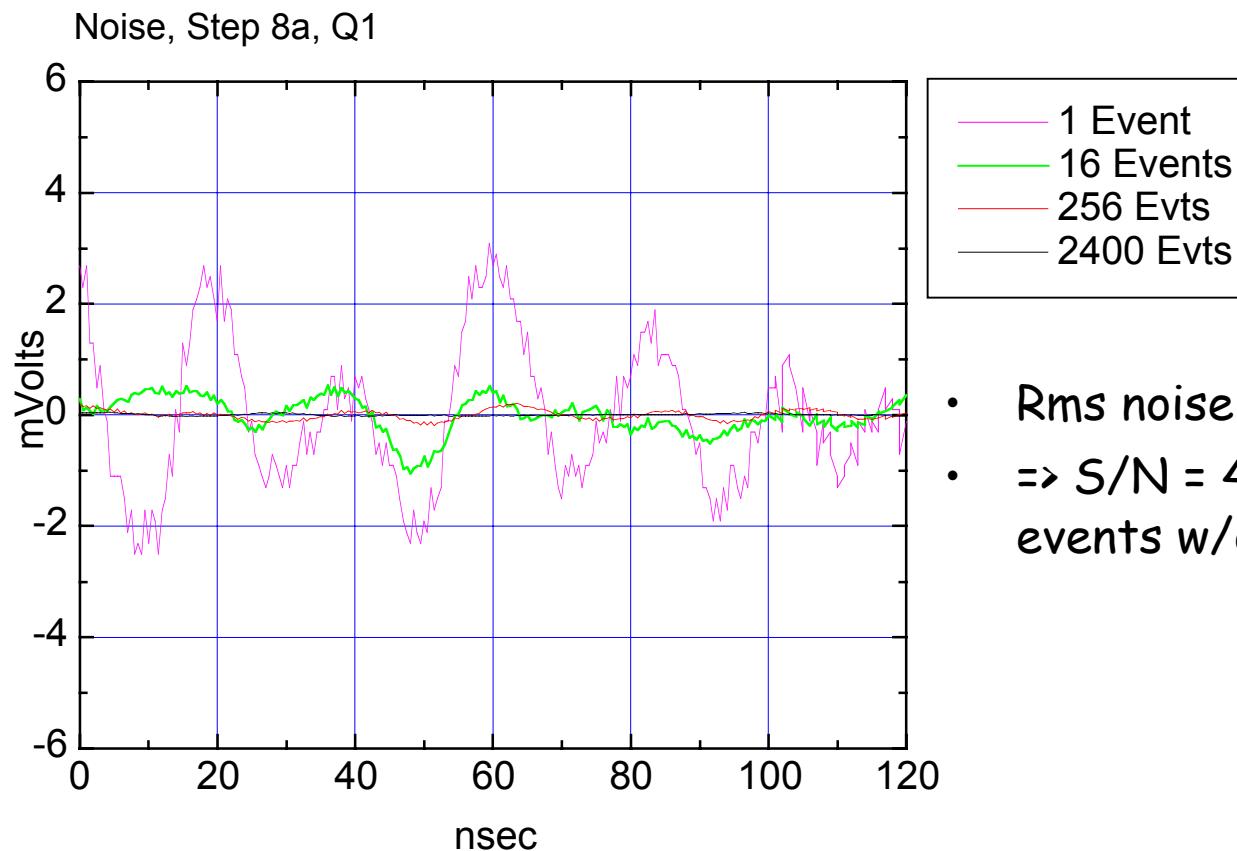
- Typical pulses, averaging, noise
- Overlay of pulse shapes, table
- What is req'd for 40MHz?
- Pulse trains
- Pressure scan
- Fe absorber thickness scan
- x/y scans through proton beam

Waveform averaging improves proton shower S/N ratio



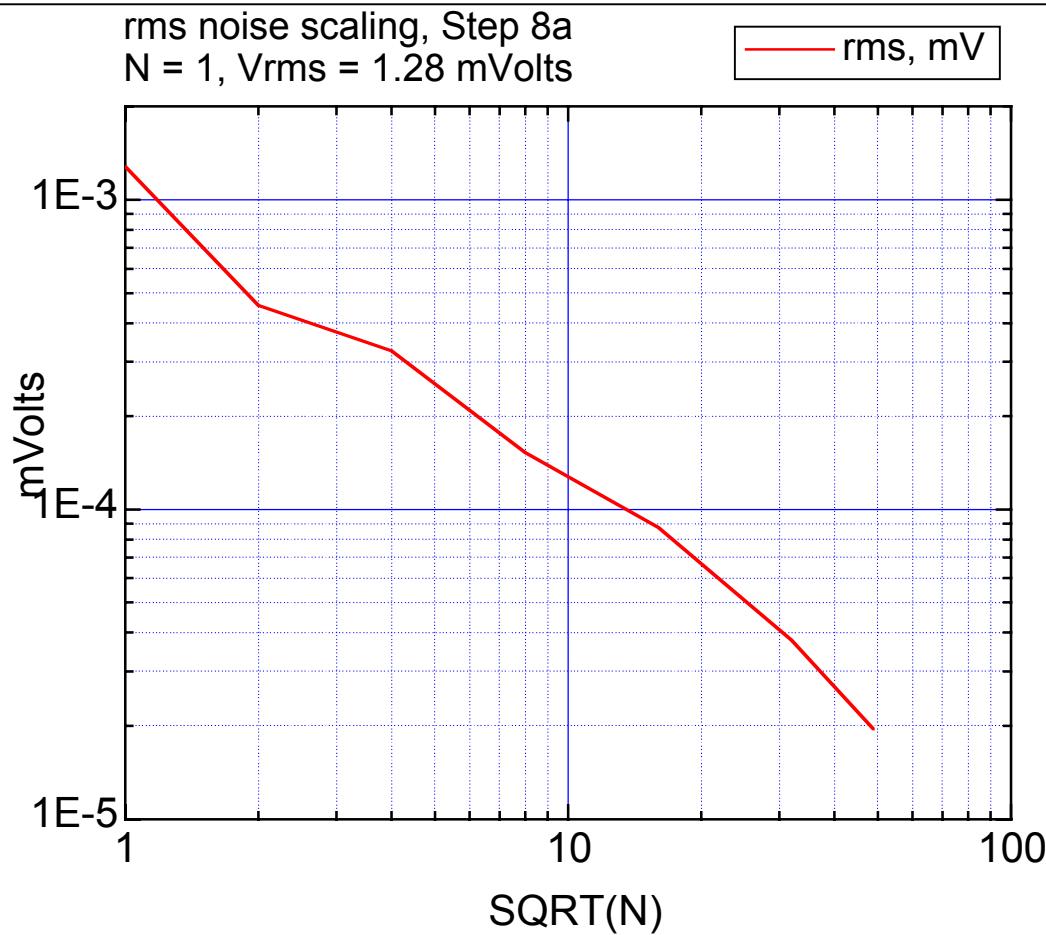
- Pulse height 4.2mV in good agreement with MARS prediction 4.0 ± 0.8 mV

Noise averages to zero



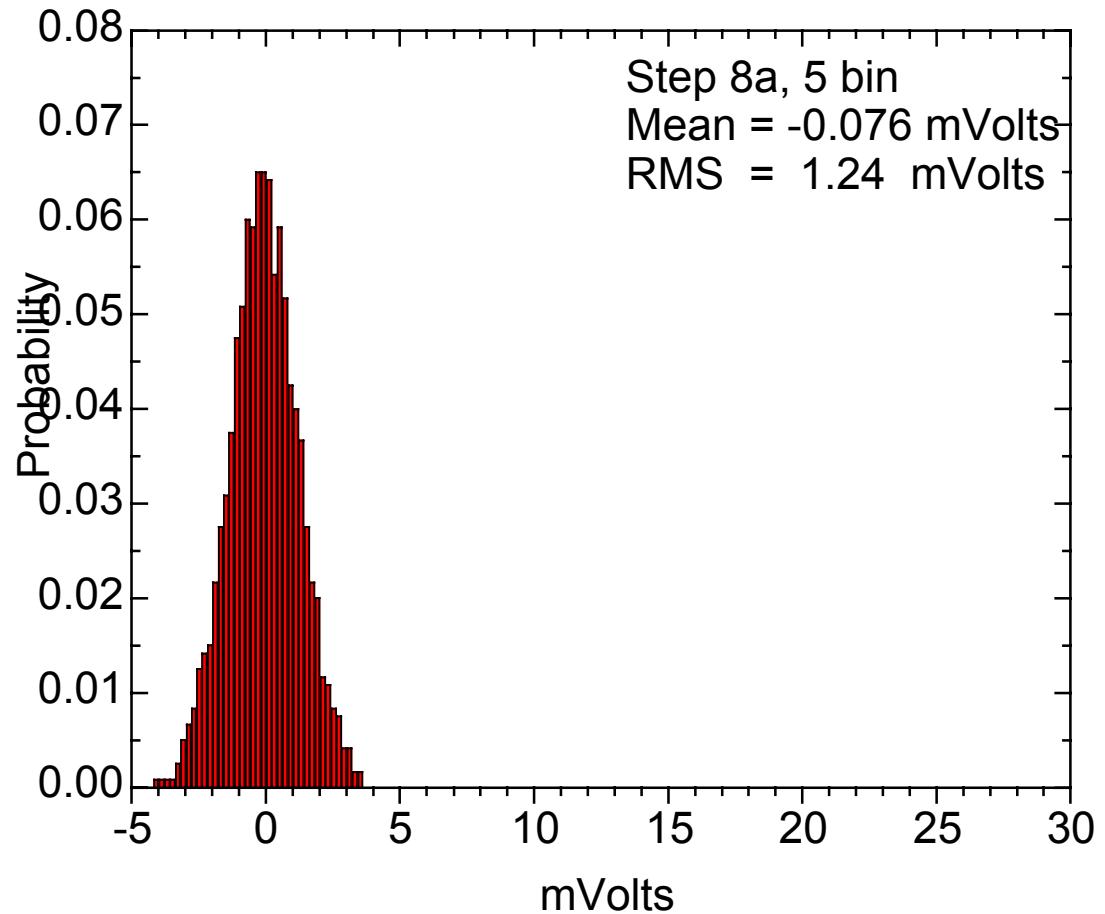
- Rms noise 1 event = 1.28 mV
- $\Rightarrow S/N = 4.2/1.28 = 3.3$ raw events w/o averaging

$N^{1/2}$ scaling of rms noise



$$\begin{aligned} ENC &= 1.28 / 0.45 \times 10^{-3} \\ &= 2,840 \text{ e} \end{aligned}$$

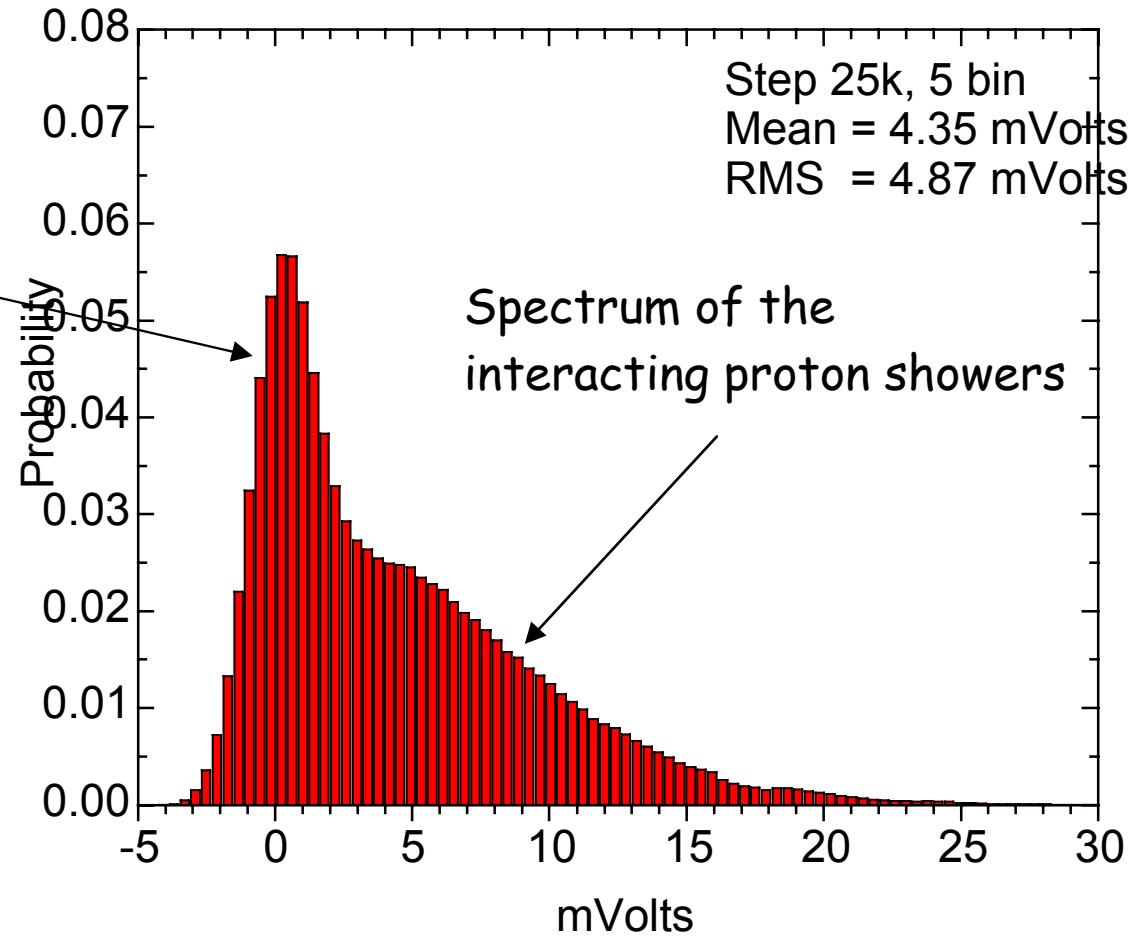
Pulse height spectrum for noise events



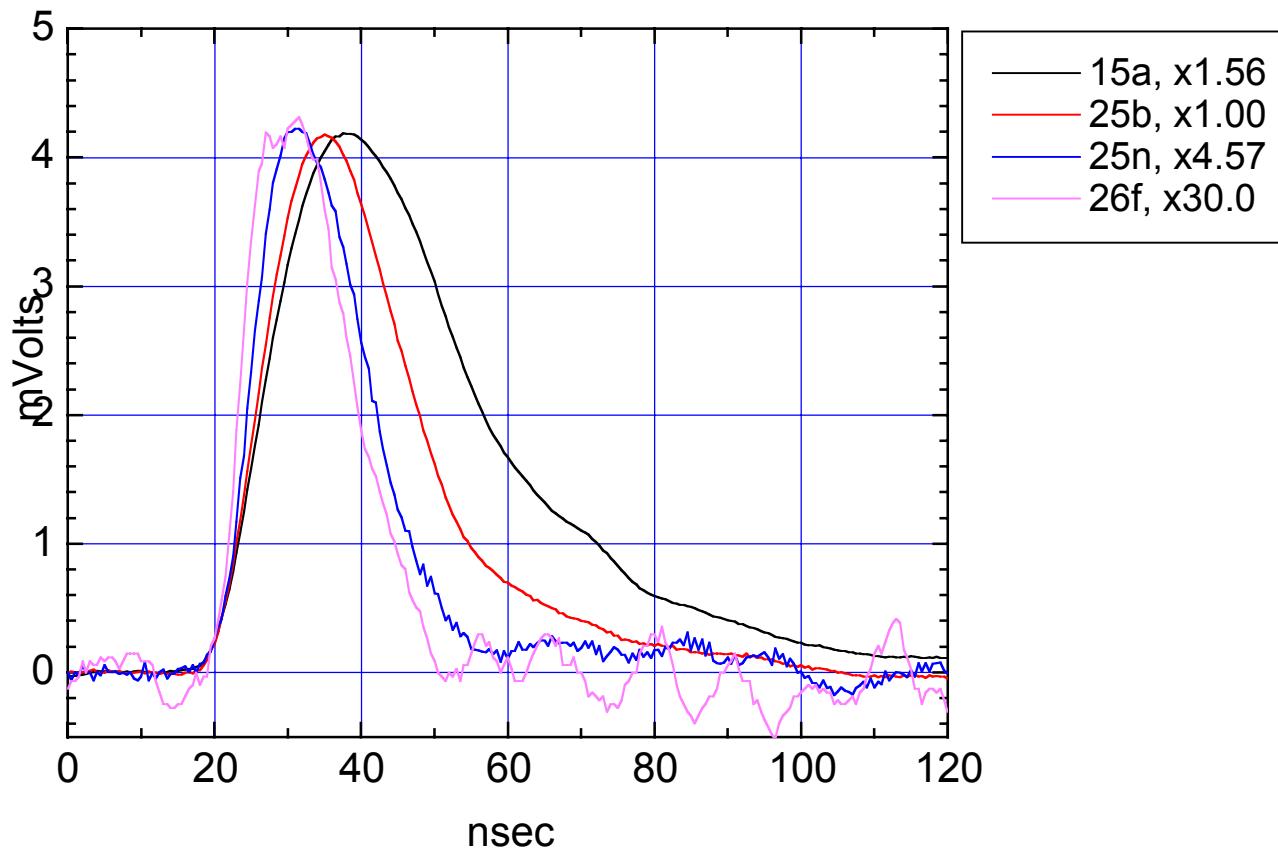
Pulse height spectrum for proton triggers

Noise spectrum due to non interacting proton fraction

$$P = e^{-\frac{z}{\lambda_{int}}}$$
$$\approx 0.33$$



A collage of waveforms with varying shape



Summary of pulse parameters for various conditions

18-Sep-01								
Summary of Pulse Parameters								
Step	Q1	Q4	Gas	P,kPa abs	Series C,pF	Pulse Height mVolts	Peak Time nsec	FWHM nsec
15a	in	in	Ar+2%N2	600	0	2.70	20.00	30.40
25b	in	out	Ar+2%N2	600	0	4.20	17.00	21.30
25n	in	out	Ar+2%N2	600	27	0.92	13.00	17.00
26a	in	out	Ar+3%N2	600	27	0.88	12.20	17.00
26d	in	out	Ar+3%N2	300	27	0.36	12.00	16.00
26f	in	out	Ar+3%N2	300	10	0.14	11.00	16.25

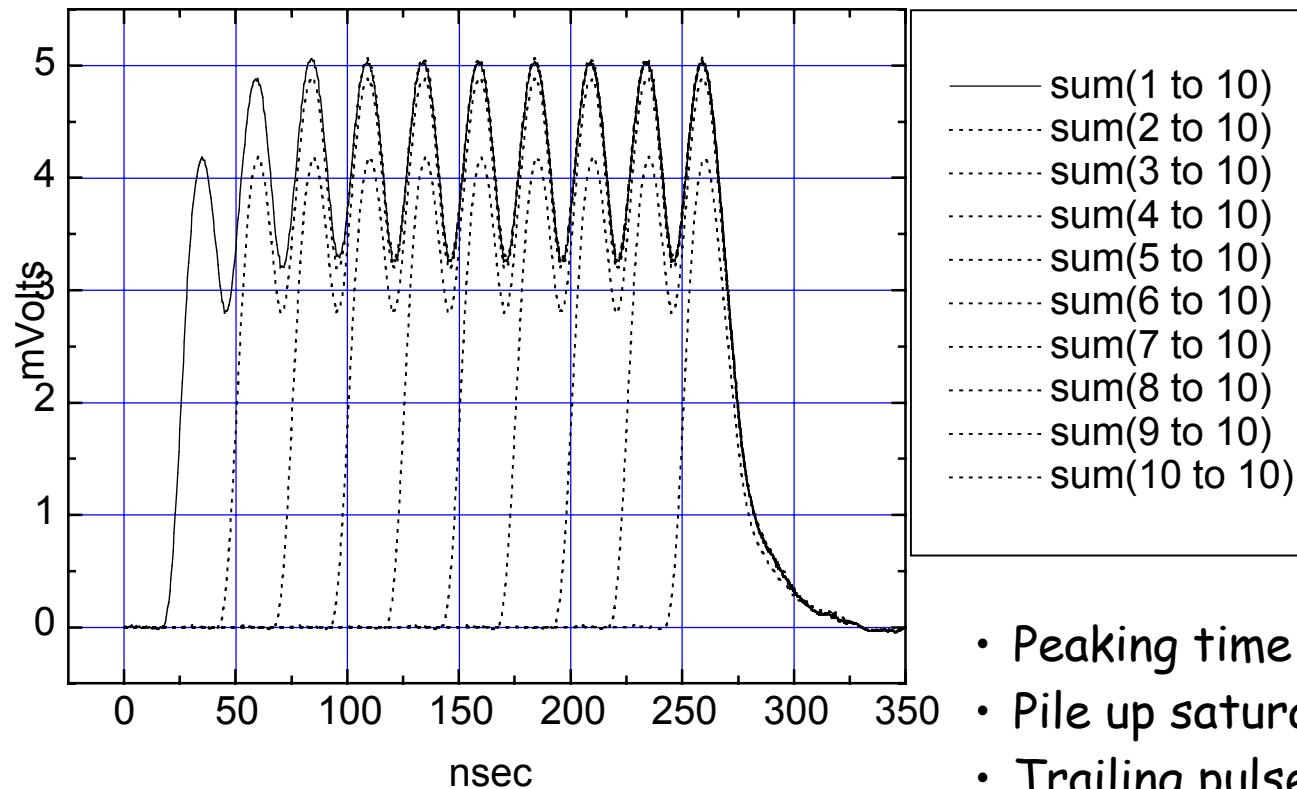
How short does the pulse need to be for 40MHz lumi measurement?

--- in general there is not a simple answer

- Full width < 25 nsec
 - No interference of bunches $V_{\text{peak}} \Rightarrow L$
- Full width < 25 ns + peaking time
 - No interference at peaks of bunches $V_{\text{peak}} \Rightarrow L$
- Peaking time < 25 ns
 - No overlap of the peak of the leading bunch in a bunch train with the trailing bunches
 - Subtraction from head to tail of bunch train deconvolves overlap
- Peaking time > 25 ns
 - subtraction from head to tail of bunch train still deconvolves overlap but more involved, accuracy of fit and propagation of noise becomes an issue

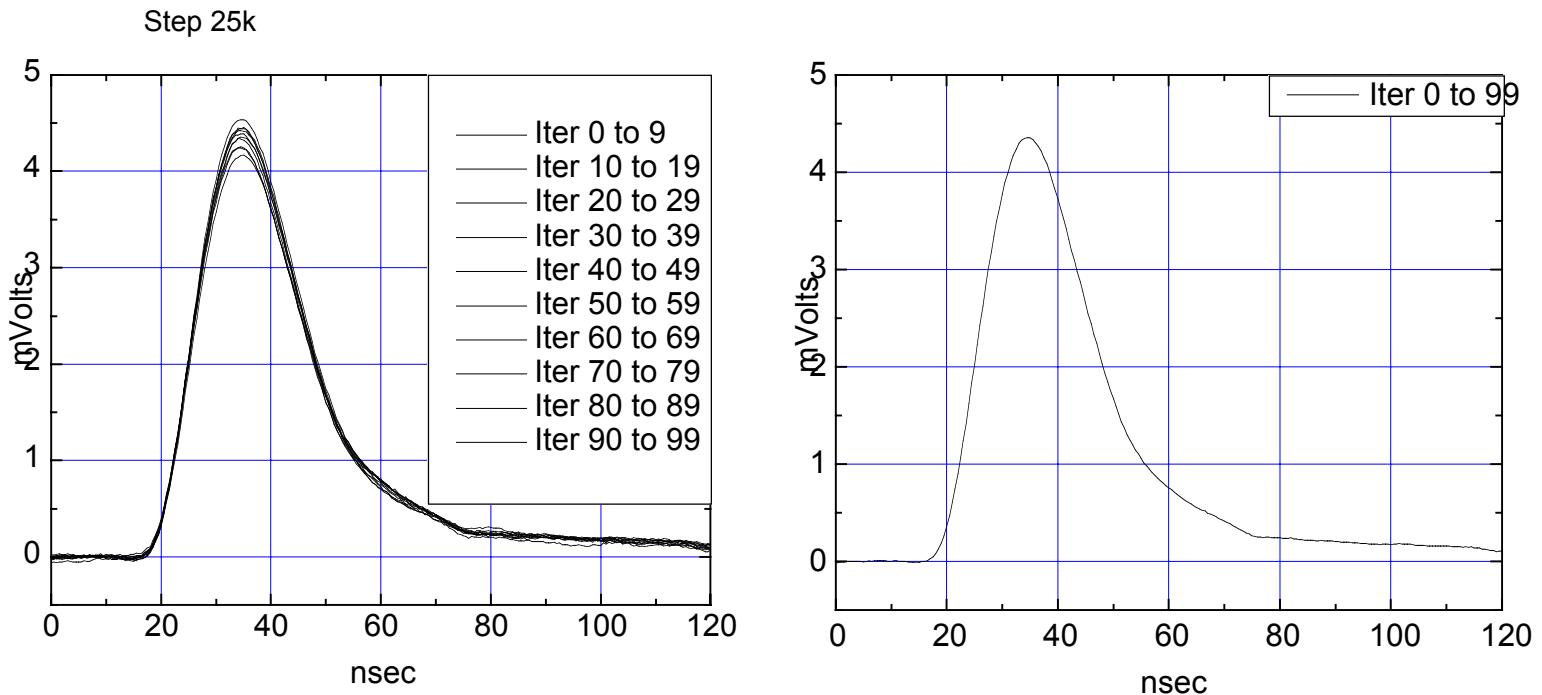
A typical proton shower waveform delayed 25 ns and added to itself 10 times

Step 25b

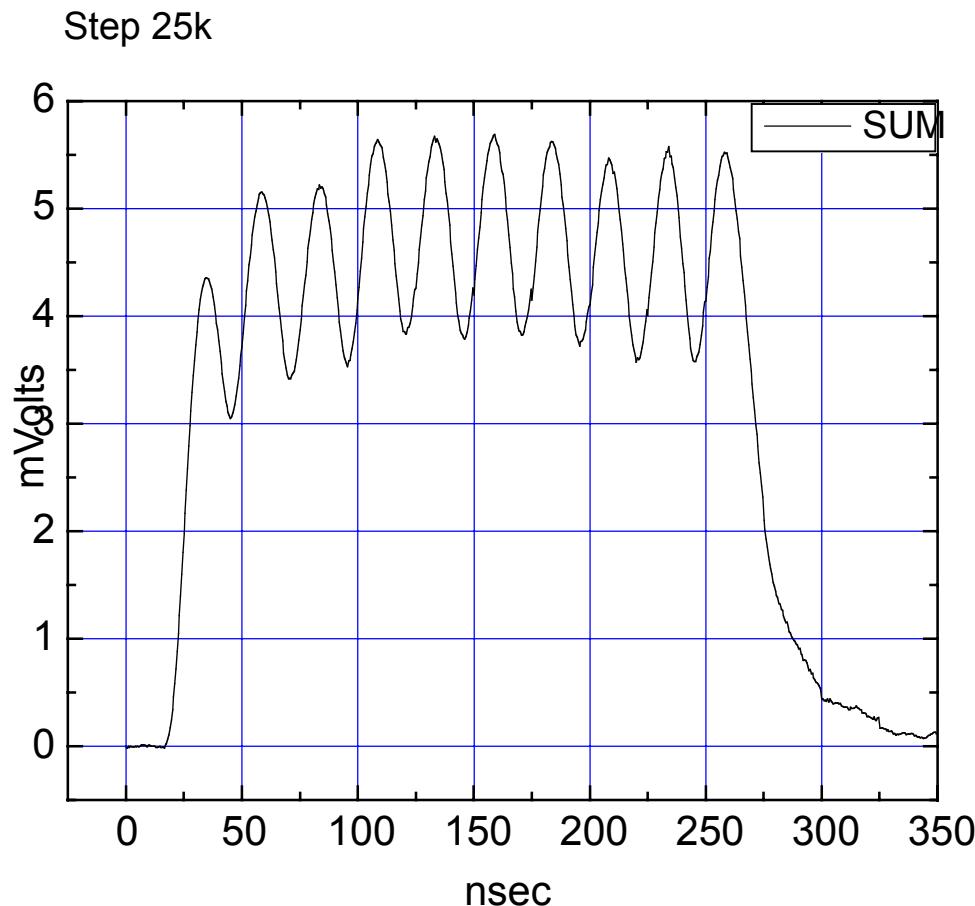


- Peaking time = 16ns < 25ns
- Pile up saturates in 3 pulses
- Trailing pulses do not interfere with the peak of the leading pulse

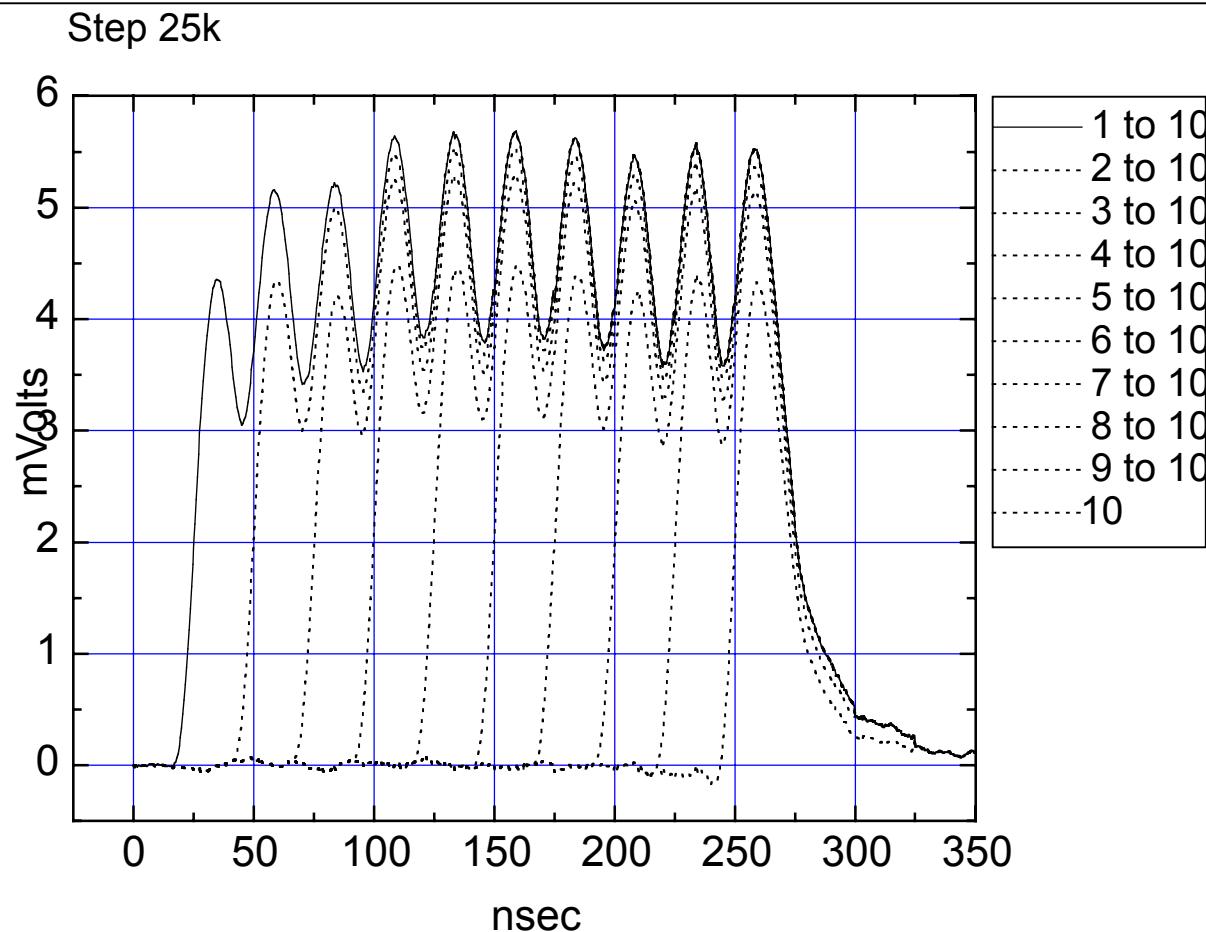
Synchronous overlay of ten 2.4k event waveforms and the 24k mean waveform



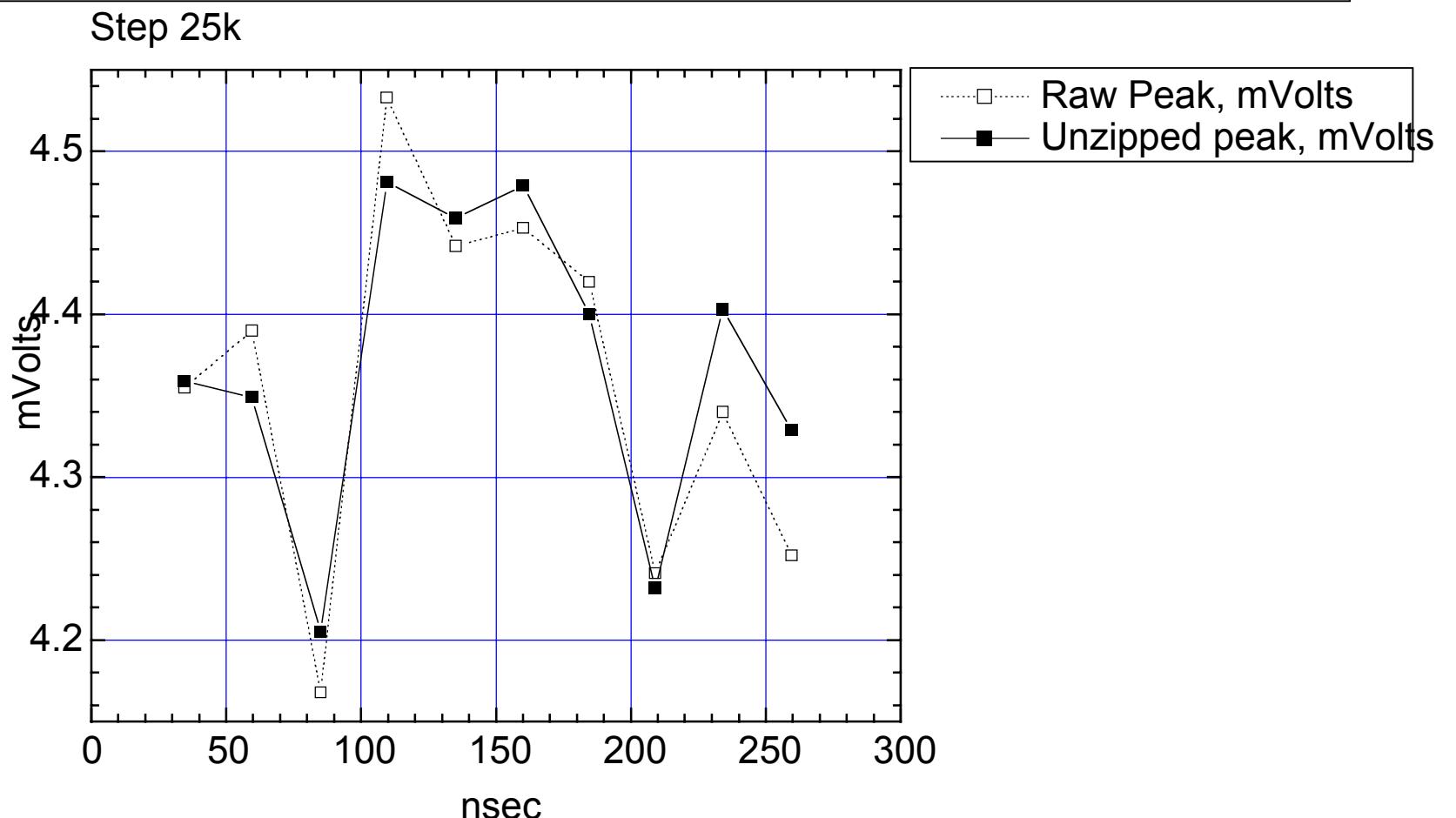
Ten pulse summation, pulses successively delayed by 25ns



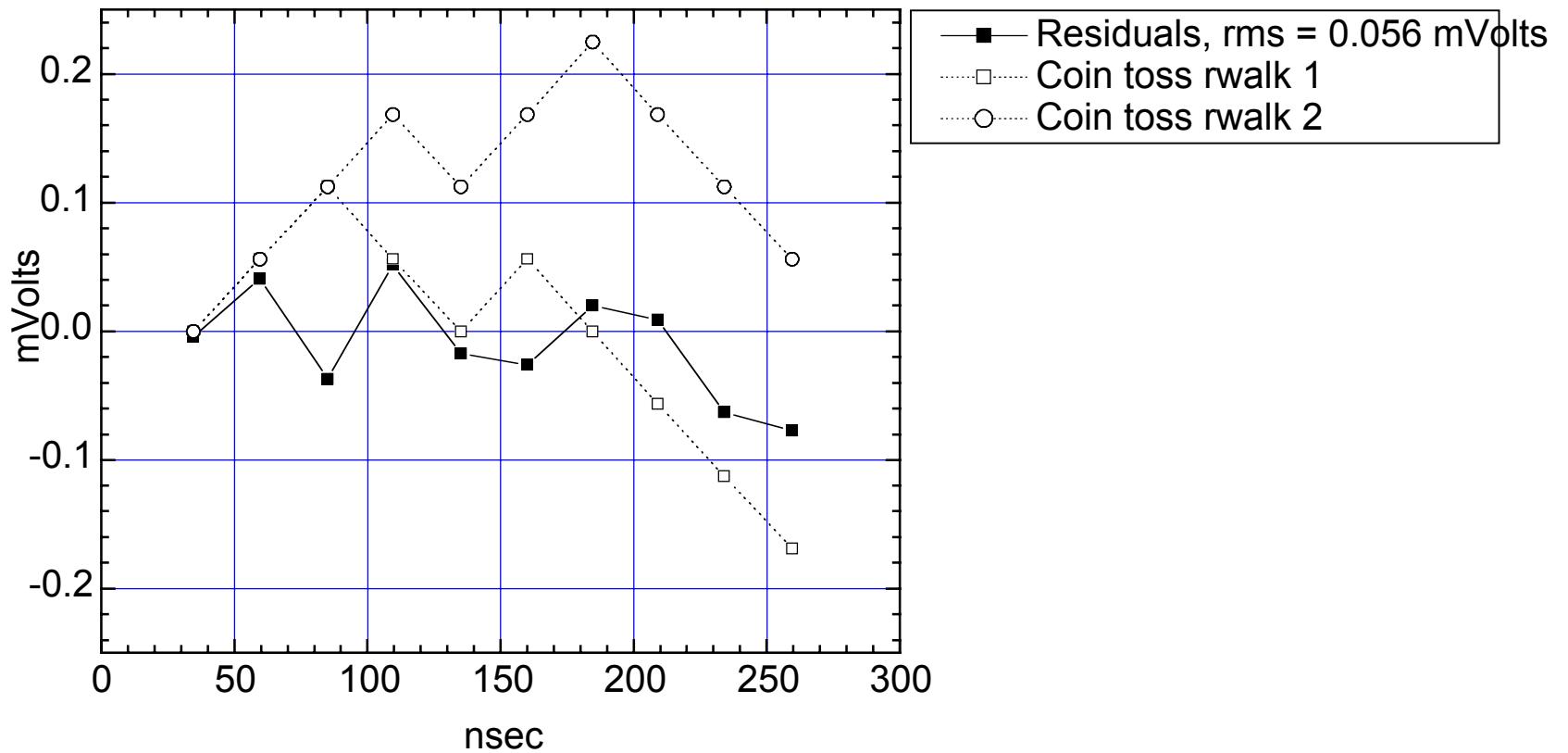
Successively fit and subtract the leading pulse



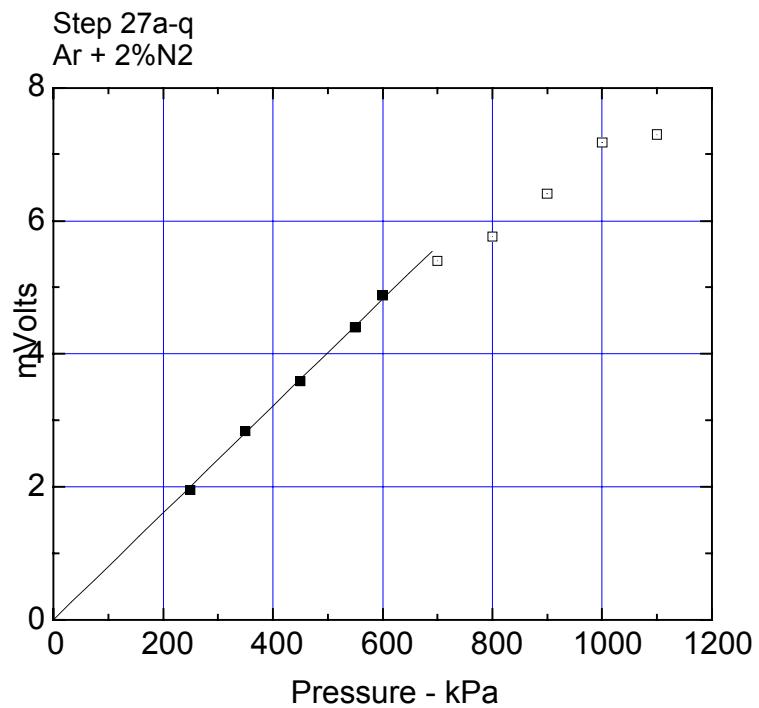
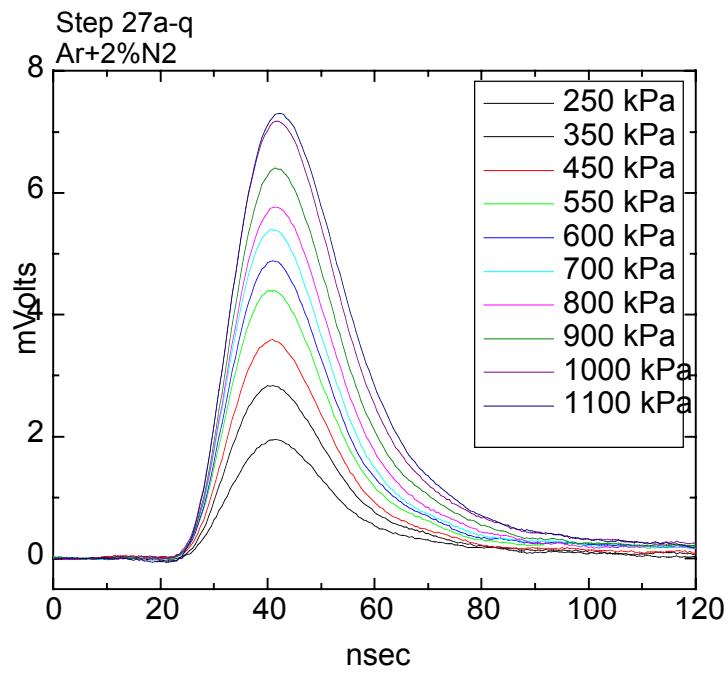
Unzipped and raw peak heights track one another
with statistical error



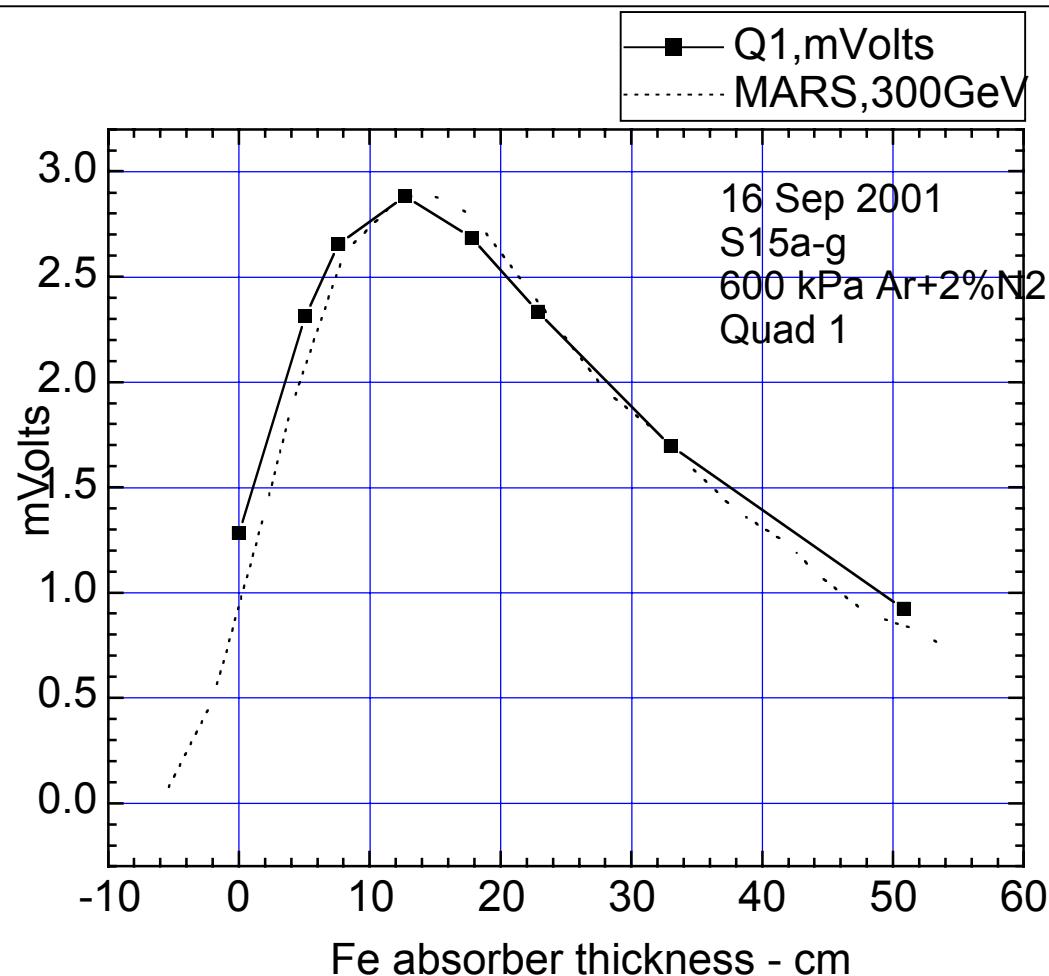
Residuals in bunch train compared to coin toss random walk



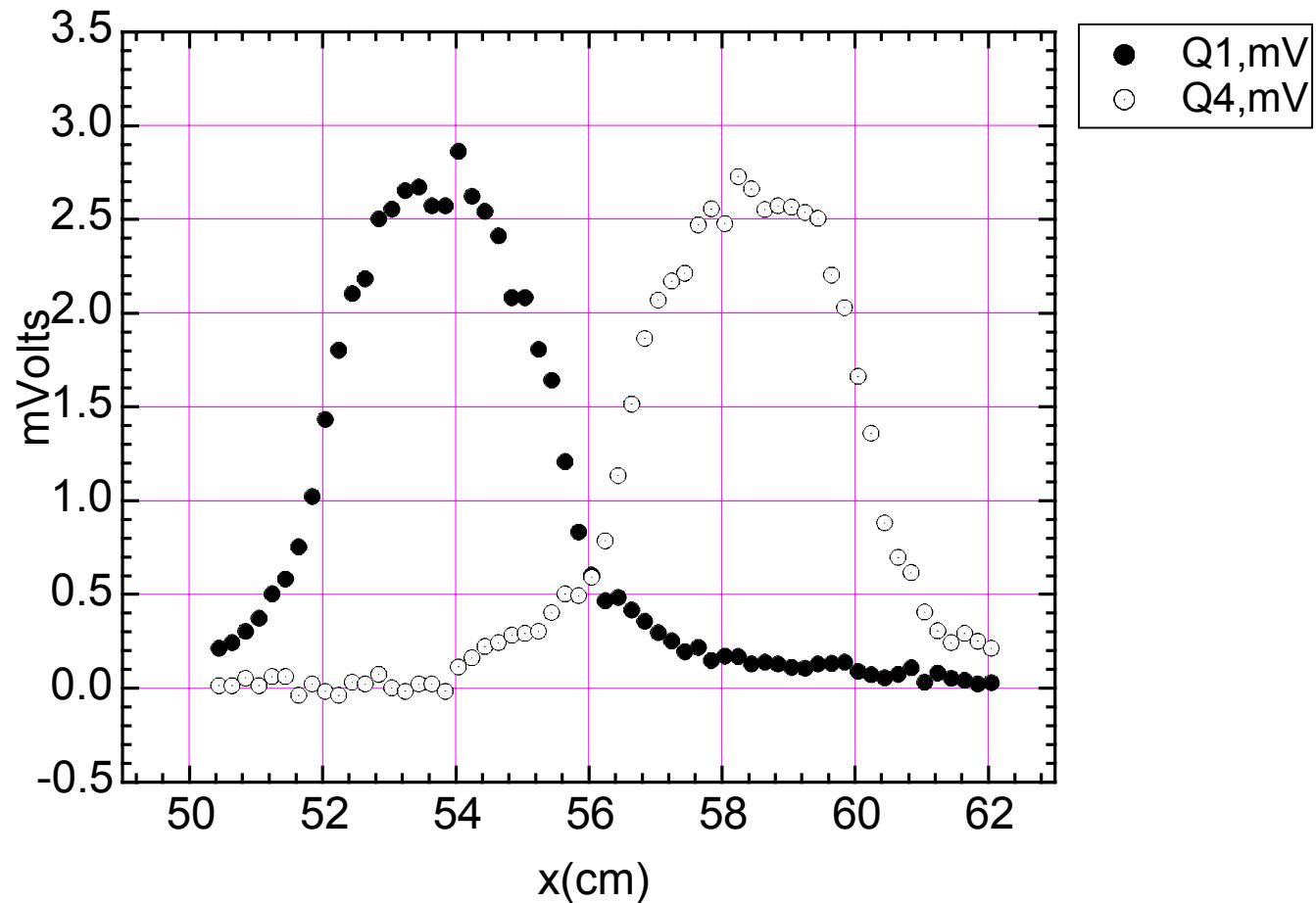
Pulse height is linear in pressure for
 $E/p > 1000 \text{ V/cm-atm}$



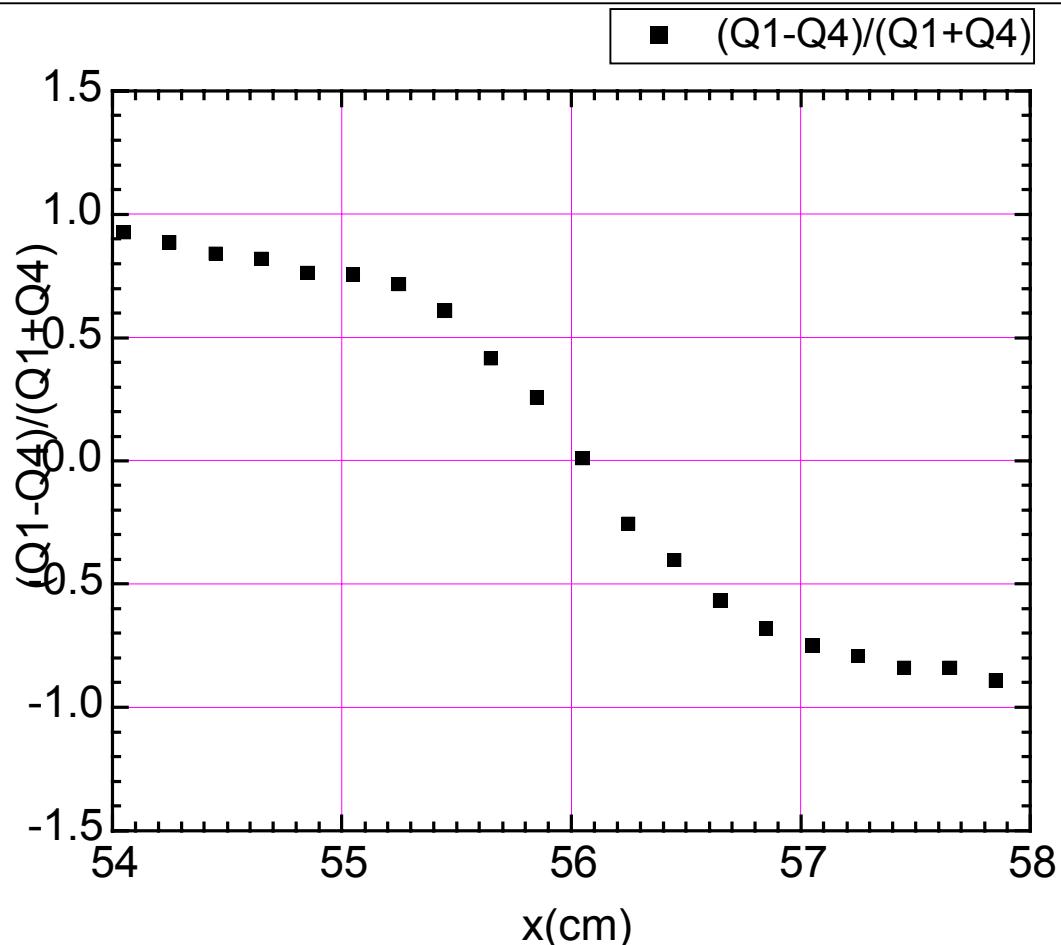
Fe absorber thickness scan, MARS data normalized to peak of experimental data



Horizontal scan of two quadrants thru proton beam

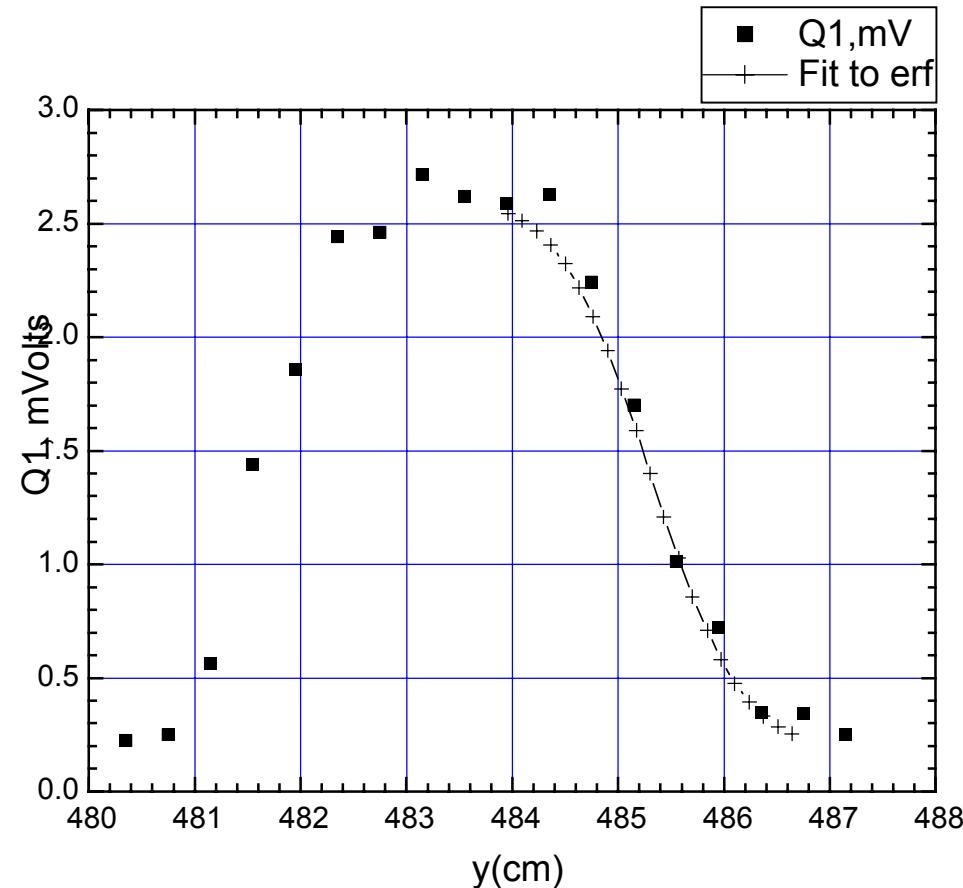


Left-right/(left+right) asymmetry defines the shower axis (crossing angle in LHC)



Vertical scan thru one quadrant

FWHM = 38 mm
ERF rms = 6.7 mm



Summary

- There is convincing evidence the ionization chamber approach to luminosity optimization of LHC can operate at the 40MHz bunch frequency and over the full range of luminosity
- 40MHz bunched beam and high radiation tests in SPS are highly desirable
- Additional understanding of parasitic impedance and of gas impurities could further reduce pulse width, although it is not necessary for 40MHz operation
- Many things are behaving as they should